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THESIS

ANALYZING SENSOR-SHOOTER LINKS THROUGH SIMULATION

by

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June 1998

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Today's military is changing. We are changing the size and structure of our forces, reevaluating our missions, and looking at military applications of new and emerging technologies. Simulation will play a key role in aiding decision-makers during these changes. This thesis demonstrates the development and use of simple, single-purpose simulation models. These models answer specific questions and can be created quickly with readily available tools. The simulation developed in this thesis is designed to serve as a basis for further studies involving the Longbow Apache. This simulation is a stochastic, process-oriented, event-step model.

To demonstrate the use of this model, a comparative analysis was performed to evaluate two field artillery "call-for-fire" procedures. Is a proposed call-for-fire procedure based on new digital technologies superior to the current process? The experiment incorporated a pre/post-process design resulting in paired observations of the artillery's effectiveness before and after incorporation of the new technology.

Results indicate the proposed procedure is superior to the current procedure. Sensitivity analysis was also performed on two input parameters as a three-by-three factorial experiment. This analysis concluded the previous results were sensitive to the specific parameter values chosen. Recommendations are made for model improvement and topics for future study.

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ANALYZING SENSOR-SHOOTER LINKS THROUGH SIMULATION

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

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Today's military is changing. We are changing the size and structure of our forces, reevaluating our missions, and looking at military applications of new and emerging technologies. Simulation will play a key role in aiding decision-makers during these changes. This thesis demonstrates the development and use of simple, single-purpose simulation models. These models answer specific questions and can be created quickly with readily available tools. The simulation developed in this thesis is designed to serve as a basis for further studies involving the Longbow Apache. This simulation is a stochastic, process-oriented, event-step model.

To demonstrate the use of this model, a comparative analysis was performed to evaluate two field artillery "call-for-fire" procedures. Is a proposed call-for-fire procedure based on new digital technologies superior to the current process? The experiment incorporated a pre/post-process design resulting in paired observations of the artillery's effectiveness before and after incorporation of the new technology.

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THESIS DISCLAIMER

The reader is cautioned that the computer program developed in this thesis may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the program is free of computational errors, it can not be considered validated. Any application of this program without additional verification and validation is at the risk of the user.

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EXECUTIVE SUMMARY

Today's military is changing. We are changing the size and structure of our forces, reevaluating our missions at global and national levels, and looking at military applications of new and emerging technologies. The main areas of technological advance include long-range precision technologies, enhanced weapon effects, low-observable technologies, and information and systems integration. The rate at which we are evaluating and acquiring these technologies indicates we are undergoing a technological revolution. The military application implies a revolution in military affairs is on the horizon.

The full impact of these advances is yet to be determined. The Army's Training and Doctrine Command (TRADOC) is exploring the impact of these technological advances and defining the requirements of the post-Cold War Army through a series of Advanced Warfighting Experiments (AWE's). This process of change has become known as "Force XXI". However, Army leaders must address numerous limitations and inter-relationships when deciding which technologies to acquire and how to best employ them. The use of simulation will be an important decision aid in these efforts. Unfortunately, many traditional simulation models are difficult to modify and not capable of reflecting future concepts and capabilities without extensive effort.

This thesis proposes an increased use of simpler, single-purpose simulation models. These models are designed to answer specific questions and can be created quickly and easily with readily available tools. The purpose of this thesis is to develop such a model and demonstrate how it can be used to answer a specific question:

Would a direct, digital link between a Longbow and a field artillery unit improve the ability of the field artillery to prosecute targets?

This question is a specific case of a much more complex issue: the time-value of information. In the demonstration case, the critical issue is the time between target detection and the time it takes an artillery unit to prosecute a target. Would decreasing this time improve the effectiveness of the artillery against a target group moving at a non-constant speed in a non-constant direction?

The simulation developed was written in Visual Basic for Applications using Microsoft Excel and models a Longbow Apache conducting a combat operation. This model serves as a basis for specific studies involving the Longbow. The structure of the model is a network design similar to event graphing: nodes represent the beginning of activities and their connecting arcs represent the passage of time. This simulation is a stochastic, process-oriented, event-step model.

This experiment incorporates a pre/post-process design. The model initially replicates the current Longbow call-for-fire procedure, which requires the aircrew to manually complete an Airborne Target Handover System (ATHS) call-for-fire. Additional subroutines are added so the model can also replicate the proposed call-for-fire procedure, which incorporates the Longbow's capability to pass targeting information by pressing two buttons. This latter procedure, referred to as a Radio Frequency Handover (RFHO), is currently used to pass targeting information digitally among Apaches in near-real time. Every artillery engagement during the simulation is first evaluated using the current Longbow procedure. The target group is then returned to its original state at the time of detection and the engagement is repeated using the

hypothesized digital procedure. This results in paired observations of the number of vehicles killed (ATHS kills and RFHO kills) and constitutes one replication. Each simulation run consists of 2,000 replications.

Hypothesis tests of the model results indicate the digital RFHO procedure is superior to the current ATHS message procedure. A direct, digital communications link between a Longbow and a field artillery unit would increase the combat effectiveness of the field artillery.

Sensitivity analysis was also performed on two input parameters: time required for completing the ATHS call-for-fire message and the lethal area of the artillery round against the notional target vehicle. This analysis was designed as a three-by-three factorial experiment using two-way, fixed effects analysis of variance. One simulation run (2,000 replications) was completed for each combination of factors for a total of 18,000 replications. This sensitivity analysis concluded that the observed differences in the numbers of vehicles killed were sensitive to both parameters.

I. INTRODUCTION

A. GENERAL

Today's military is changing. We are changing the size and structure of our forces, reevaluating our missions at global and national levels, and looking at military applications of new and emerging technologies. One may say we are currently undergoing a technological revolution as we rapidly experiment with advances in numerous technological areas to determine their impact on the conduct of future combat. The rate at which we are evaluating and acquiring these technologies indicates we are preparing to radically change the way we conduct military operations. The current technological revolution implies a revolution in military affairs is on the horizon.

The main areas of technical advance include long-range precision technologies, enhanced weapon effects, low-observable technologies, and information and systems integration. The Army's Training and Doctrine Command (TRADOC) is exploring the impact of these technological advancements and defining the requirements of the post-Cold War Army through a series of Advanced Warfighting Experiments (AWE's). Within the Army, this process of change has become known as "Force XXI".

The focus of Force XXI is "Army XXI", the "digitized" Army of the year 2010 that incorporates the Chairman of the Joint Chiefs of Staff's *Joint Vision 2010*. However, this Army will only be a stepping stone to the desired end state: "Army After Next". This Army will be characterized by full spectrum dominance and a new conceptual framework consisting of four emerging operational concepts: dominant maneuver, precision engagement, full dimensional protection and focused logistics. The basis for this new

conceptual framework will be improved command, control, communications, computers and intelligence (C4I) providing significant information superiority.

B. PROBLEM

Improving C4I does not come without limitations. Multi-level security (MLS) classifications, bandwidth limitations, economic feasibility, and information accuracy and timeliness are some of the hurdles military leaders must address when deciding which technologies to acquire and how to best employ them. How can leaders make timely decisions given the multitude of options and limitations?

Without doubt, simulation will continue to play an important role in support of the decision making process. Numerous Department of Defense (DoD) regulations and directives now call for increased use of modeling and simulation. Within the acquisition community for example, former Undersecretary of Defense for Acquisition and Technology, P.G. Kaminski, required the Simulation, Test and Evaluation Process (STEP) be an integral part of Test and Evaluation Master Plans [Ref. 1]. The underlying approach to this process is a repetitive cycle of modeling, testing, and then modeling again to incorporate the test results.

This streamlined process is in keeping with current acquisition reform efforts such as the Warfighting Rapid Acquisition Program (WRAP). The WRAP was established in April of 1996 to "accelerate [the] fielding of systems and technology that emerge from successful ... Advanced Warfighting Experiment's (AWE's), Advanced Technology Demonstrations, Advanced Concept Technology Demonstrations or similar demonstrations and evaluations" [Ref. 2]. The use of simulation will allow thorough,

timely, and cost efficient analysis of equipment and technologies identified for WRAP; as well as reduce the time, resources, and risks of the acquisition process.

However, acquisition is not the only community to embrace simulation. Large-scale simulation models such as JANUS assist decision-makers looking at organizational changes; future operating concepts; and tactics, techniques, and procedures (TTP's). Simulation is also prevalent at the numerous TRADOC Battle Labs which explore future concepts and technology.

Unfortunately, many traditional simulation models are difficult to modify, require extensive scenario development, and are not capable of reflecting future concepts and capabilities without an enormous amount of effort. Additionally, creating new simulation models of similar scope is too costly in terms of time and money, especially considering that organizational and doctrinal changes of the Army are uncertain. Therefore, traditional, large-scale simulation modeling may not always be feasible.

Perhaps part of the solution to this problem lies in the use of simpler, single-purpose models. These models are designed to answer specific questions. A military analyst could create such a model in a relatively short period of time on a desktop computer to provide an initial look at a complex issue or to rapidly explore excursions. One could say this is the new generation of "back of the envelope" analysis.

C. PURPOSE

The goal of this study is to develop a combat simulation model that is capable of modeling specific aspects of combat systems interactions quickly and easily with readily

available tools. The purpose is to show how such a model can be used in answering questions similar to the following:

Would a direct, digital communications link between sensor A and weapon system B improve the ability of weapon system B to prosecute targets?

D. SCOPE

The purpose of this effort is not necessarily to answer this or any other particular question of interest; but, it will demonstrate a technique for deriving an answer through the use of simulation. In particular, this study will address the question above by looking at the one specific sensor-shooter link: the link between a Longbow Apache and a field artillery unit where the Longbow Apache is acting as the sensor for the artillery. This scenario is one specific example of a much large issue: the impact of information timeliness.

The following chapter provides a brief background of the Force XXI effort and the Army's command and control systems. Chapter III discusses the development of the model used in this study and steps through a sample run. Chapter IV demonstrates an approach to analyzing the specific sensor-shooter link mentioned, including sensitivity analysis of two key parameters. Chapter V addresses recommendations for model improvements and future study.

II. BACKGROUND

A. FORCE XXI

In the early 1990's, the collapse of the Soviet Union and increasing federal budget deficits led to rapid military force reductions. Facing further reductions, then-Secretary of Defense Les Aspin directed a Bottoms-Up Review (BUR) of the military in 1993. That review concluded that additional reductions were possible while still achieving national security objectives: maintain a global presence and be prepared to engage in two major regional conflicts simultaneously [Ref. 3, p. 1].

At the same time, then-Army Chief of Staff GEN Gordon R. Sullivan endorsed "digitization", the incorporation of advanced communications and computer technology in any redesign efforts. "Digitization involved linking combat elements with high-speed, sophisticated computers, enabling forces to share situational awareness and allowing commanders to distill battlefield information into rapid, accurate tactical decisions" [Ref 3, p. 4]. This would enhance the mobility, flexibility, and firepower of the Army.

TRADOC Commander GEN Fredrick M. Franks (soon to be succeeded by GEN William W. Hartzog) was assigned the responsibility of linking the Army's digitization and experimentation efforts and subsequently initiated the Advanced Warfighting Experiments (AWE's) in March of 1994. The purpose behind these AWE's was to use "real soldiers, in real units, early in the design process to provide immediate insights into future force requirements" [Ref. 3, p. 5]. This experimentation/redesign process was similar to the High Technology Light Division experiments initiated in 1981 that resulted

in the short-lived 9th Infantry Division (Motorized). The "Experimental Force" (EXFOR) for the AWE's was, and still is, the 4th Infantry Division located at Fort Hood, Texas.

The "Force XXI" effort was officially initiated on March 8, 1994 by GEN Sullivan. This term describes the overall redesign process of the institutional and operational Army. Force XXI, through the AWE's, will examine the impact of current technological trends on the conduct of future warfare. Army XXI will incorporate the resulting changes in force structure; doctrine; and tactics, techniques, and procedures (TTP's) as it transitions into the Army After Next.

B. TECHNOLOGICAL TRENDS

Joint Vision 2010 identifies technological trends in four primary areas that influence the future of the Armed Forces: long-range precision, weapon effects, low-observables, and information and systems integration [Ref. 4, p. 11-15].

- Improvements in long-range precision capabilities continue as a result of improving global positioning systems, increasing standoff capabilities, and continued high-energy and electromagnetic research. Advances in this area mean more weapon systems will be able to engage targets at greater ranges and with greater accuracy than in the past, enhancing economy of force and increasing the operational tempo.
- A broader range of weapon effects will increase the options available to commanders in combat or other operations.
- Advances in low-observable technologies will likely lead to numerous changes. Signature reduction, stealth, and "micro-miniaturization" will increase the survivability of friendly forces operating during day or night anywhere on the battlefield. This has profound implications on

the element of surprise and further enhances economy of force, as fewer forces may be required to accomplish a mission. Also, multi-spectral sensing, sensor fusion, and automated target recognition will increase the ability to detect enemy targets at greater ranges and under worse conditions than in the past.

- Advances in information and systems integration technologies such as data fusion and information management are primarily the result of evolving communications technologies and improving computer processing. These advances will lead to commanders and soldiers at the front line having more information in a more timely manner, allowing them to make better decisions. Advances in this area will lead to "dominant battlespace awareness", influencing all aspects of combat and other operations.

Although these advances are all interrelated, this study focuses on only the last trend: information and systems integration.

C. EMERGING OPERATIONAL CONCEPTS

The technological trends addressed above will have a profound effect on future warfare; but, their full impact is not yet completely understood. The AWE's and other exercises continue to explore the possibilities. *Joint Vision 2010* provides four "emerging operational concepts" [Ref. 4, p. 20-26]:

- *Dominant Maneuver* – the multidimensional application of information, engagement, and mobility capabilities to position and employ widely dispersed joint air, land, sea, and space forces to accomplish the assigned operational task.
- *Precision Engagement* – a system of systems that enables our forces to locate the objective or target, provide responsive command and

control, generate the desired effect, assess our level of success, and retain the flexibility to reengage with precision when required.

- *Full-Dimensional Protection* – control of the battlespace to ensure our forces can maintain freedom of action during deployment, maneuver, and engagement, while providing multi-layered defenses of our forces and facilities at all levels.
- *Focused Logistics* – the fusion of information, logistics, and transportation technologies to provide rapid crisis response, to shift assets even while enroute, and to deliver tailored logistics packages and sustainment directly at the strategic, operational, and tactical level of operations.

These emerging concepts serve as the new conceptual framework for future operations.

D. INFORMATION SUPERIORITY

"The basis for [this] framework is found in the improved command, control and intelligence which can be assured by information superiority" [Ref. 4, p. 19]. Referred to as "dominant battlespace knowledge" in some texts, information superiority is defined as "the capability to collect, process, and disseminate an uninterrupted flow of information while exploiting or denying an adversary's ability to do the same" [Ref. 4, p. 16].

To fully understand this definition, one must realize that a significant difference exists between data, information, and knowledge. Data that are correlated or synthesized becomes information; information that is converted into situational awareness becomes knowledge; and knowledge used to predict consequences of actions leads to understanding [Ref. 5, p. 89]. Figure 1 displays this concept.

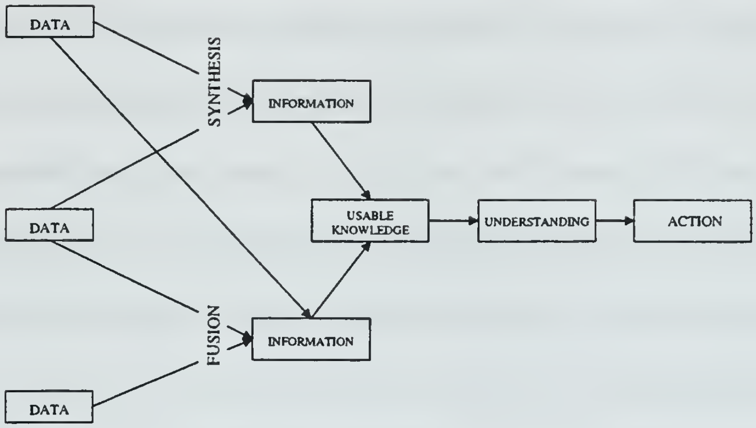

Figure 1. Hierarchy of Information

As an example, advanced technology now allows data received from strategic level resources at the operational level of the Army's command structure to be rapidly fused or synthesized into information and then useable knowledge as it is automatically passed to lower command levels. This will allow more command levels to have a better understanding of the current battlespace. Thus, obtaining information superiority is defined as having a greater understanding of what is occurring within a multi-dimensional battlespace in less time than our enemy does, as Figure 2 illustrates.

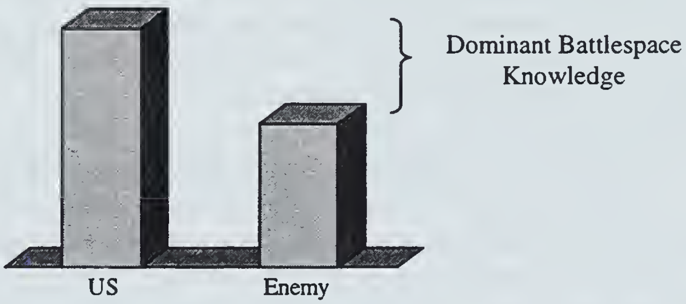

Figure 2. Level of Battlespace Understanding

Information superiority does not mean that all soldiers and all units will have complete information. That is an unrealistic ideal. Current and future intelligence sensors

and weapon systems such as tactical unmanned aerial vehicles (TUAV's), ground-based common sensors (GBCS), and Comanche can not provide complete data or information to all participants at all times. Like most major systems, these are limited in number, subject to reliability and maintainability problems, and have some degree of inaccuracy. A realistic goal for obtaining information superiority is to ensure the right warfighter has the right information at the right time.

E. ARMY COMMAND & CONTROL SYSTEMS

The Warfighter Information Network (WIN) is the Army's proposed information system that will integrate communications and information services and provide a linkage from strategic level resources, through the operational levels of command, to front line soldiers. An important information system within WIN is the Army Battlefield Command System (ABCS) which functionally links all Army headquarters between the operational and tactical levels of command and serves as the operational interface with the Global Command and Control System (GCCS) at the strategic level (Figure 3). This system will likely serve as the Army's entry point for most of the data and information received from strategic and operational level resources.

The ABCS is comprised of three components: the Army Global Command and Control System (AGCCS) for the theaters and echelons above corps, the Army Tactical Command and Control System (ATCCS; later to become the Army Battle Command System) for corps through maneuver battalion headquarters, and the Force XXI Battle Command Brigade and Below (FBCB2, formerly *applique*) for brigade headquarters through platform level. In addition to fusing and synthesizing raw data, each of these

systems will receive and distribute information and data based upon numerous factors such as security classification of the information, age of the information, and its applicability to the intended receiver.

The ATCCS consists of five Battlefield Functional Area Control Systems to help manage the flow of information. These systems are based upon the traditional Battlefield Operating Systems (BOS) and include the following:

- The All Source Analysis System (ASAS)
- The Maneuver Control Station/Phoenix (MCS/P)
- The Advanced Field Artillery Tactical Data System (AFATDS)
- The Combat Service Support Command and Control System (CSSCS)
- The Forward Area Air Defense Command, Control and Intelligence System ($FAADC^2I$)

All five systems will communicate amongst themselves through a local area network and with similar systems at different echelons through an information network. Together, these systems provide a common operating picture (COP) that addresses all battlefield operating systems.

The FBCB2, a developmental system being evaluated and refined during the AWE's, manages information flow among all systems within the brigade. Its primary purpose is to extend the flow of information, in near-real time, down to the individual soldier level through tactical communications systems linked by common Internet protocols and routers. These integrated systems form the Army's "Tactical Internet". Through the Tactical Internet, the systems above will get the right information to the right soldiers at the right time.

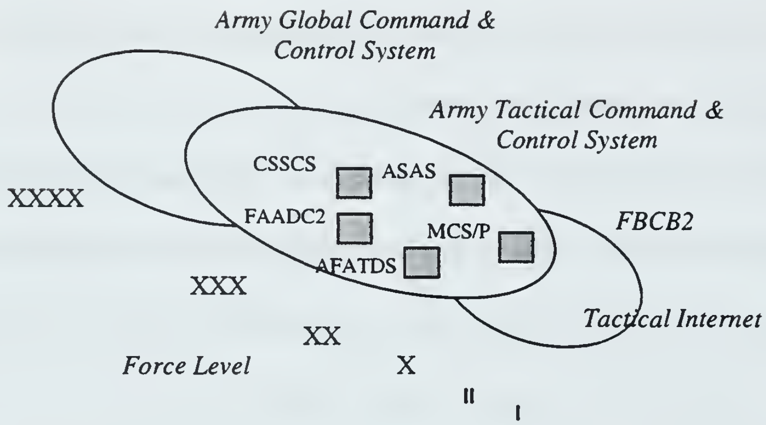

Figure 3. The Army Battle Command System

F. LIMITATIONS

Unfortunately, exploiting information and systems integration technologies does not come without limitations. Bandwidth limitations and multi-level security classifications are some of the realities that will restrict the quantity and timeliness of information available to soldiers at the front lines [Ref. 6]. The ability to efficiently manage and fuse the large volume of data and information expected is also likely to hinder information flow. The use of "push" and "pull" information technologies will help insure information gets to the right people at the right time; but, these technologies currently depend on detailed user profiles that do not dynamically change with the tactical scenario of the user. Advances in global satellite communications capabilities (Direct Broadcast System/Battlefield Awareness Data Dissemination System) are likely to improve the timeliness and quantity of the flow of some types of information. However, economic constraints will probably limit the use of these technologies at the tactical, especially platform and system, level. In the end, not all weapon systems may be

able to exploit the latest digitized capabilities by communicating in a system-to-system manner. Leaders must decide which systems should have this capability.

Which systems should be "digitized"? Clearly, there is no easy answer. The impact of advances in information and systems integration technologies across the battlefield is staggering. Technological advances in other areas, systemic limitations, and an uncertain future only confound the problem.

G. MODELING & SIMULATION

Perhaps part of the solution lies in the use of small, single-purpose simulation models: models designed to answer specific questions. A military analyst could create such a model in a relatively short period of time on a desktop computer to provide an initial look at a complex issue or to explore additional options.

In a previous study, a simulation model was used to demonstrate the benefits of digitized communications over non-digitized communications in the command, control and communications systems associated with the Extended Fiber Optic Guided Missile (EFOGM). Using a semi-Markov chain, the study demonstrated that the digitized communications reduced the time a call-for-fire waited in a queue, resulting in missions being fired more rapidly with more targets being destroyed [Ref. 7]. In a similar manner, this study demonstrates how to evaluate a sensor-shooter communications link through the use of a stochastic simulation model.

The choice of analyzing the Longbow Apache serving as a sensor for the artillery arose out of personal curiosity. Arguably, the Longbow Apache, hereafter referred to as just the Longbow, is one of the most digitized platforms on the battlefield. Within

seconds its millimeter-wave radar can detect, identify, and prioritize dozens of targets at ranges out to eight kilometers. If the crew decides to engage one of the highest priority targets, they can launch a Longbow Hellfire missile within seconds of detection. The crew also has the option of passing these targeting data to another Apache[1] over a secure radio. This process is referred to as conducting an "RFHO" (Radio Frequency Handover) and is accomplished by pressing two buttons. Receipt of an RFHO enables the receiving Apache to launch a Hellfire missile within seconds at a target that was detected by a Longbow.

However, to send these data to an artillery unit to engage the target with indirect fires, the aircrew must manually enter the data in a pre-formatted message using an awkward keypad. This text-based process, dating back to the early eighties, is known as the Airborne Target Handover System (ATHS). This "call-for-fire" process is time consuming and subject to human error.

This study provides a simulation model that examines the impact of expanding the RFHO capability of the Longbow to include the field artillery's AFATDS. Specifically, this study compares the combat effectiveness of the artillery (measured by the expected number of vehicles destroyed) under two types of call-for-fire systems: the current ATHS and an RFHO-capable system.

However, this application of the RFHO capability to the AFATDS is not an original concept presented by the author. Efforts are currently underway to define a Joint Variable Message Format (JVMF) that will prescribe the standard formats for all

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[1] The term "Apache" is used to indicate a D-model Apache without the Longbow radar.

messages among all services. When this is implemented, the Longbow's call-for-fire message will be sent to the AFATDS in a manner similar to the RFHO method. This study demonstrates a method to examine the potential impact of this effort as it pertains to the effectiveness of the field artillery and a Longbow.

III. MODEL DEVELOPMENT

A. GENERAL

The model developed in this study is a stochastic, process-oriented, event-step model of a Longbow conducting a combat mission. The model is written in Visual Basic for Excel. By definition, a stochastic model incorporates uncertain occurrences by drawing random observations from known distributions [Ref. 8, p. 3]. Examples of such occurrences include target location errors, ballistic errors of artillery rounds, and the times required to complete specific events. The Visual Basic function *rnd* () is used to draw random values from the Uniform (0,1) distribution. These values are occasionally used to create random observations from Normal distributions (using the polar transformation method) and Weibull distributions (using the inverse transformation method). Random draws from an Exponential distribution are also easily obtained from the Weibull distribution, since the Exponential distribution is nothing more than a special case of the Weibull distribution.

Unlike many simulation models, this model is process-oriented. The more common method of event-scheduling considers time to be a continuous value, as does a process-oriented approach. Both methods also use an event list to manage the sequence of event occurrences and the time advance mechanism. However, unlike event-scheduling models, a process-oriented model explicitly represents the passage of time, allowing the simultaneous execution of several different processes [Ref. 8, p. 17]. For example, the Longbow may continue to detect targets while the artillery unit is firing rounds at another target, or the Longbow may receive an information update while searching for targets.

Two programming languages were considered in developing this model: Visual basic for Excel and Java. Visual Basic for Excel was chosen as the programming language for several reasons. First, due to the large number of input parameters, the ability to name these parameters on Excel worksheets and then use these names directly in the subroutines was most appealing. Likewise, the network structure of the model was easy to manipulate on worksheets. Managing the sequence of events was also easier to incorporate using an Excel worksheet as the event list and the Visual Basic *sort* () function to sort the events in the proper time sequence. Finally, the availability and common use of Excel makes this model more attractive to those who may wish to use or expand it without having to learn Java. Even individuals who are not familiar with Visual Basic can manipulate the model parameters on the worksheets and obtain useful results.

B. APPROACH

Because a model is an abstraction of a real system, activities and interrelationships may be modeled explicitly, implicitly, or not at all. Those activities pertaining to the purpose of the study are explicitly developed in greater detail than other activities. To examine the Longbow-Artillery communications link, those aspects of the system that influence the artillery-related activities are modeled in detail. These include target vehicle movement; preparing, transmitting and processing the call-for-fire; firing the artillery rounds; and evaluating the effectiveness of each round against the target. Other aspects are modeled explicitly, but in less detail, to facilitate follow-on efforts and to provide realism to the simulation.

Some aspects of reality are modeled implicitly. The effects of uneven terrain, weather and battlefield obscurants on target detection are accounted for in the stochastically derived detection ranges of the target vehicles. When the target vehicles are initialized, they are assigned a random "detected at" range based on the impact of environmental effects on detection probabilities. A searching Longbow will detect the enemy if the distance between these two entities is less than that range. A short range indicates the target is well hidden by terrain, weather conditions or some other feature and is difficult to detect. A long range indicates the opposite. Human factors such as fear, excitement, and fatigue are also implicitly modeled. These factors are incorporated in the model as longer times to complete tasks and/or higher probabilities of committing errors.

C. ASSUMPTIONS

As with most simulations, numerous assumptions are required to transform a complex, real-world process into a computer simulation. The most critical assumptions required in this study include the following:

- The ballistic error of the artillery rounds can be modeled using a Bivariate Normal distribution, independent in the *x* (deflection error) and *y* (range error) directions and independent from round to round.
- All target vehicles are of the same type and a Gaussian lethality function is appropriate for artillery rounds against these vehicles.
- The enemy target groups are caught by complete surprise; they have no knowledge of impending danger. As an aside, the Crusader weapon system will feature a Multiple Round

Simultaneous Impact (MRSI) capability, allowing each howitzer to fire up to eight rounds that will impact simultaneously [Ref.9].

- The tactical scenario is such that the artillery unit is "waiting" for a call-for-fire from the Longbow. No attempt has been made to account for the fact that fire missions may be delayed in a queue due to mission overload, priority of fires, unit readiness, or the like. While previous studies have shown this assumption to be unlikely [Ref. 7], it is still reasonable for the purposes of this particular study.
- The time required for the AFATDS to process and forward a call-for-fire is the same for an ATHS message and an RFHO.
- Enemy detections of the Longbow, aircraft malfunctions and receipts of information are independent, random events.

Additionally, the parameters entered in the model do not necessarily reflect the true values. Most values represent the professional opinion of the author based on personal experience or educated guesses from others. All values are unclassified, and any resemblance to classified data is purely coincidental. (Personnel who enter classified data into this model should consult with their security manager or representative for handling instructions.)

D. STRUCTURE

1. General

The model design is best described as a directed node-arc network. The nodes represent specific events (beginning of activities) and the arcs indicate the possible events that may be scheduled next, most likely after some specified time delay. Graphical

representation of this type is frequently referred to as "event graphing" [Ref. 10, p. 72]. Time is represented as a cost associated with occupying a specific node or traversing a specific arc. These values may be either stochastic or deterministic. Not all nodes and arcs have associated time costs. A subroutine named "*Run*" serves as the engine for the model, coordinating movement through the network. Figure 4 illustrates the flow of activities included in this model using an abbreviated event-graph format.

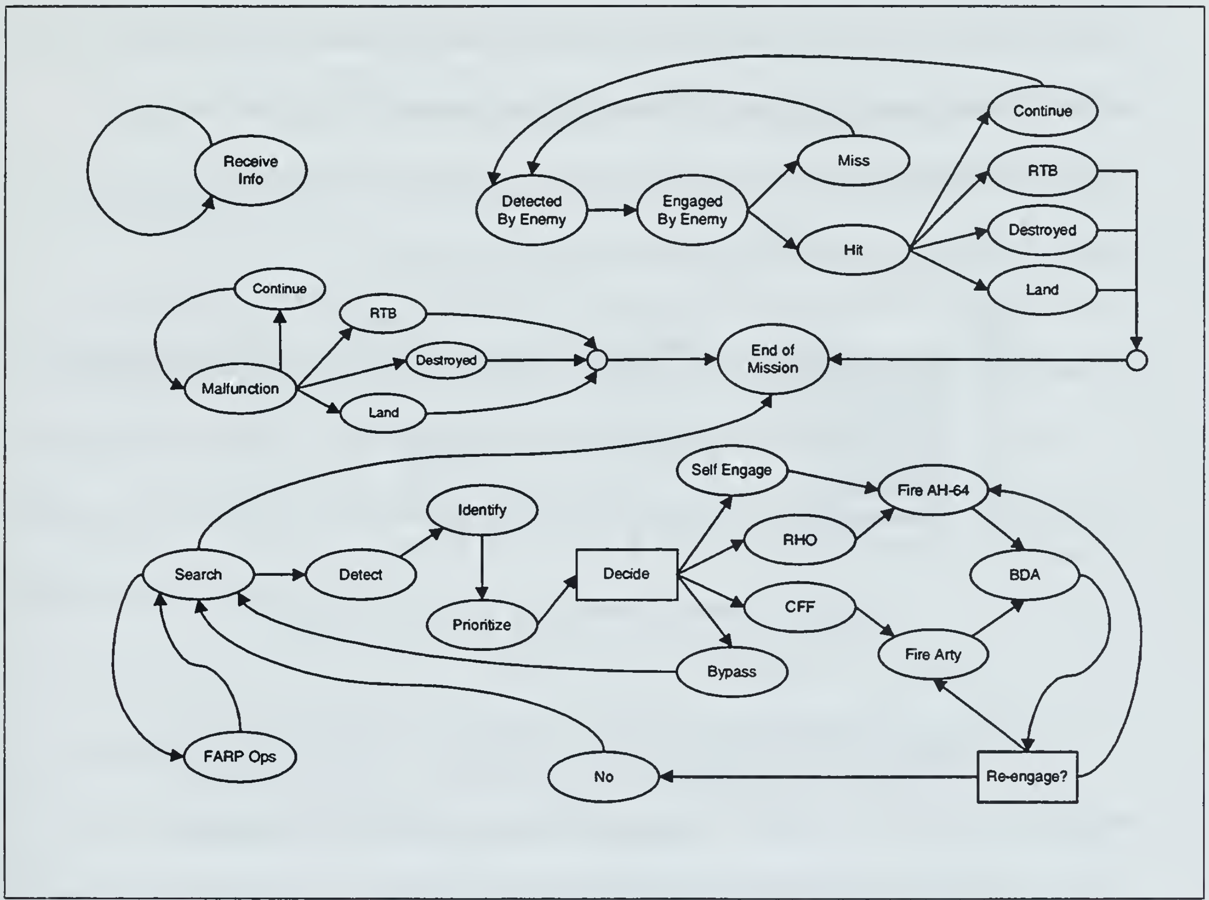

Figure 4. Simulation Flow

2. Networks

Instead of attempting to manage one large network, the model is divided into several smaller networks. Each of these smaller networks is maintained on a separate Excel worksheet that contains all the information necessary to traverse that network: node number, time spent occupying a node (cost), adjacent node numbers, probabilities associated with adjacent nodes and any additional time spent between nodes (arc costs). The times may be fixed values or may include calls to random number generators for a Uniform, Normal, or Weibull (including Exponential) random times. Node numbers may include a sheet name to indicate a link to a different network. The worksheet also maintains individual node names and the node's out degree (number of arcs leaving the node). A sample of a network worksheet is shown in Figure 5.

Sample		Out				Connected to ...					
Node #	Name	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost
15	Preparing RFHO	2	U	1	2	16	0.9	0	23	0.1	0
16	Sending to AFATDS	2	7	0	0	18	0.95	0	17	0.05	0
17	AFATDS not rec'd	1	0	0	0	20	1	10			
18	AFATDS rec'd	2	0	0	0	22	0.85	0	19	0.15	0
19	Reject (error)	1	10	0	0	20	1	0			
20	Aircrew notified	1	N	10	2	15	1	10			
21	Evaluating (Fail)	1	5	0	0	20	1	0			
22	Evaluating (Success)	1	5	0	0	Arty	1	0			

Figure 5. Sample Network on an Excel Worksheet

The model consists of seven networks: *Longbow, Artillery, Apache, FARP, Malfunction, Detected,* and *Info*. These networks are displayed in Appendix A. The primary network is the *Longbow* network, which models the Longbow under its current configuration conducting a "normal" mission. The other networks are merely extensions of this network:

- *Artillery* - an artillery unit firing at a specific target after receiving a call-for-fire.
- *Apache* - an Apache that receives a target handover from a Longbow.
- *FARP* - a Longbow occupying a Forward Arming and Refueling Point. (While FARP is the more commonly used acronym, this point is doctrinally referred to as a Forward Area Rearming/Refueling Point or "FARRP").
- *Malfunction* - a Longbow experiencing a malfunction.
- *Detected* – actions taken when an enemy detects a Longbow.
- *Info* – a Longbow receiving information from an external source.

3. Worksheets

The model uses Excel worksheets to manage data and record parameters. A total of 15 worksheets are in the "basicEvent.xls" workbook. Eight of these sheets are used for management and seven maintain the network information as described above. The following list briefly describes each management sheet. All management worksheets are displayed in Appendix B.

- *Menu* – allows the user to input the number of "runs", provides an option for printing the sequence of events on the *Output* sheet, and contains the "*Run*" command button. The current run number is displayed while the simulation is running.
- *Parameters* – maintains all user-defined parameters for the artillery, target, and Longbow entities.
- *Output* – if the option for output is chosen on the *Menu* sheet, this sheet will display the time that each event began, the name of the event and the network sheet name and node number of the event.

- *Stats* – displays the mean, standard deviation, maximum value and minimum value for user defined statistics. The current configuration displays statistics on the size of detected enemy target groups, the number of vehicles that are killed by artillery fires per engagement using the ATHS, and the number of vehicles that are killed by artillery fires per engagement using the RFHO system.
- *Friendly* – maintains information regarding the current state of the friendly entities.
- *Enemy* - maintains information regarding the current state of the enemy entities.
- *DetectList* – maintains a list of enemy target groups currently detected by the Longbow.
- *EventList* – the schedule of events to occur in the future.

4. Subroutines & Functions

Not visible are the subroutines and functions associated with the nodes. When an arrival at a node occurs, the *Run* subroutine looks for and executes any subroutines associated with that node. For example, the subroutine *endMission* is associated with a specific node in a specific network. When an arrival to this node occurs, this subroutine clears the event list and schedules an "End of Mission" event to occur. Some subroutines call other subroutines and some change values in the network worksheets.

The following is a brief description of the subroutines and functions used in this simulation. The subroutine's associated network and node or the calling subroutine is shown in parentheses. A more detailed explanation of the ***bold*** subroutine/functions can be found in Appendix C.

- ***"Run"** Subroutine* – controls the flow of the simulation (initiated by clicking the "Run" command button on the *Menu* worksheet).

- ***"initiateSheets"** Subroutine* – prepares worksheets at the beginning of the simulation (called by *Run*).

- ***"nextNode"** Subroutine* - determines the next node (activity) to add to the event list (called by *Run*).

- ***"setPositions"** Subroutine* - defines and records the starting locations and conditions for all enemy and friendly entities (called by *Run*).

- ***"Move"** Subroutine* - moves all entities that have a speed greater than zero (called by *Run*).

- ***"atWayPoint"** Subroutine* - adjusts the aircraft's course toward the next waypoint, schedules the next *"atWayPoint" event*, and reschedules all detections (*Longbow*, node 28).

- ***"schedDetect"** Subroutine* - evaluates all entities to determine if a friendly unit will detect an enemy unit (*Longbow*, nodes 1, 11, 13, 18, 22, 23, 25; Malfunction, node 7; *atWayPoint*).

- ***"solveQuad"** Subroutine* - returns the time values that are solutions to the quadratic equation used to schedule detections and "un-detections". An un-detection refers to the time at which a friendly unit is no longer able to detect the enemy. Together, these times define the "detection window" for the Longbow. (called by *schedDetect*).

- *"unDetect" Subroutine* - removes a specific enemy entity from the *DetectList* sheet at the un-detect time (see above) to indicate the entity is no longer being detected (*Longbow*, node 29).

- *"clearDetect" Subroutine* - removes all detected events from the event list, unless the current event is a detection (*Longbow*, node 2; *Malfunction*, nodes 2-6; *atWayPoint*).

- "***detection***" *Subroutine* - records all pertinent information: enemy identification number, time, location, and rate and direction of movement (*Longbow*, node 2).

- "*Prioritize" Subroutine* - prioritizes all detections on the *DetectList* based upon range (*Longbow*, node 7).

- ***"predictXY"*** *Subroutine* - predicts the *x* and *y* coordinates of the target at the time artillery rounds will impact (*Artillery*, node 8).

- ***"shootArty"*** *Subroutine* - simulates the firing and impact of artillery rounds (*Artillery*, node 8).

- *"howManyRnds" Function* - returns the number of rounds to fire at a specific target group based upon user-defined parameters in the "Artillery" section of the *Parameters* worksheet (*Artillery*, 6).

- *"setTimeOfFlt" Subroutine* - determines the time of flight of the artillery rounds in seconds based upon user-defined values in the "Artillery" section of the *Parameters* worksheet (*Artillery*, 6).

- *"getBE" Subroutine* - returns the range and deflection ballistic errors for an artillery round based upon user-defined values in the "Artillery" section of the *Parameters* worksheet(*shootArty).*

- "***BDA*** " *Function* - returns a boolean indicating whether a specific artillery round has "killed" a specific enemy vehicle (true) or not (false) (*shootArty*).

- *"countKills" Function* - returns the number of vehicles that have been killed in a specific enemy target group (*Artillery*, 8).

- *"sortEventList" Subroutine* - sorts the elements of the event list based upon increasing time of occurrence (*Run*).

- *"getDistance"*(x_1, y_1, x_2, y_2) *Function* - returns the distance (in meters) between the two coordinates (as required).

- *"getAngle"*(x_1, y_1, x_2, y_2) *Function* - returns the angle (in radians) between two vectors defined by (x,y) coordinate pairs using the *Atn* () function (as required).

- *"**Norm**"(mean, standard deviation) Function* - returns one random observation from a normal distribution having the given parameters (as required).

- *"**Weibull**"*(α,β) *Function* – provides random observations from a Weibull distribution with parameters α and β (as required).

- *"endMission" Subroutine* - clears the *eventList* and schedules an "End of Mission" event to occur (*Longbow*, 30; *Malfunction*, 11).

E. EXAMPLE RUN

First, the user must verify the parameters on the *Parameters* worksheet are correct. This example uses those values displayed on the worksheets in Appendix A. The user then inputs the required number of runs and clicks the "Run" command button on the *Menu* worksheet to initiate the *Run* subroutine, hereafter referred to as "*Run*". *Run* begins the simulation by defining certain variables, initiating the worksheets (*initiateSheets* subroutine), and setting the friendly and enemy positions (*setPositions* subroutine). The *Friendly* and *Enemy* worksheets now display the initial states of the entities as shown in Figures 6 and 7.

ID #	Type	#	X - Coord	Y- Coord	Speed	Radians	Degrees	Detected at Range	Detected	Killed? 1	2	3	4	5	6	7
1	Longbow	1	07500	00000	61.728	5.650	324	N/A	N	N	N	N	N	N	N	N

Figure 6. *Friendly* Worksheet (Time = 0.00)

						Direction		Detected		Killed?						
ID #	Type Tgt	# Veh	X - Coord	Y- Coord	Speed	Radians	Degrees	at Range	Detected	1	2	3	4	5	6	7
1	IFV	3	02809	08651	3.479	1.793	103	2191	N	N	N	N	N	N	N	N
2	IFV	4	08311	12760	3.715	3.409	195	2721	N	N	N	N	N	N	N	N
3	IFV	5	02531	08122	3.738	1.788	102	2357	N	N	N	N	N	N	N	N
4	IFV	6	13506	12087	2.970	1.632	93	2666	N	N	N	N	N	N	N	N
5	IFV	5	01947	07547	2.932	3.770	216	2736	N	N	N	N	N	N	N	N

Figure 7. *Enemy* Worksheet (Time = 0,00)

These subroutines have also scheduled events on the event list. These events correspond to the random events that may occur at any time in the simulation: aircraft malfunctions, detections by the enemy, and the receipt of information. Figure 8 displays the current event list.

Begin Time	Event	Sheet	Node	Param 1	Param 2	Param 3	Param 4
0.00	Searching	Longbow	1				
150.67	At Waypoint	Longbow	28				
924.35	Receiving Info	Info	1				
4188.88	Detected by Enemy	Detected	1				
30459.56	Malfunction	Malfunction	1				
999999.00	End						

Figure 8. ***EventList*** **Worksheet (Time = 0.00)**

The simulation then enters the network with the current time equal to zero by evaluating the first event on the event list: the "Searching" event, corresponding to node 1 from the *Longbow* network. *Run* then searches for any subroutines associated with this specific node. The code below shows that *Run* calls the *schedDetect* subroutine when the current sheet name (sName) is "Longbow", the current node (atNode) equals one, and the time equals zero.

```
Select Case sName
   Case "Longbow"
      Select Case atNode
         Case 1                    'Searching
            If (time = 0) Then Call schedDetect(ByVal time)
```

schedDetect schedules detections and un-detections on the event list. The updated event list is displayed in Figure 9. The values in the "Param 2" column indicate which group is detected or un-detected at that specific time. Several subroutines use this value later.

Begin Time	Event	Sheet	Node	Param 1	Param 2	Param 3	Param 4
0.00	Searching	Longbow	1				
150.67	At Waypoint	Longbow	28				
924.35	Receiving Info	Info	1				
4188.88	Detected by Enemy	Detected	1				
30459.56	Malfunction	Malfunction	1				
999999.00	End						
128.72	Friendly 1 Detects Group 1	Longbow	2		1		
172.47	Friendly 1 UnDetects Group 1	Longbow	29		1		
114.55	Friendly 1 Detects Group 3	Longbow	2		3		
178.11	Friendly 1 UnDetects Group 3	Longbow	29		3		
106.22	Friendly 1 Detects Group 5	Longbow	2		5		
192.41	Friendly 1 UnDetects Group 5	Longbow	29		5		

Figure 9. ***EventList*** **Worksheet (Time = 0.00; after** ***schedDetect*****)**

With no other actions required, *Run* then determines the next event to schedule by calling the *nextNode* subroutine. *nextNode* draws a random number from the Uniform (0,1) distribution (0.058 in this case) and compares it to the cumulative probabilities of the adjacent nodes listed on the *Longbow* network. The node at which the cumulative probability exceeds the random number becomes the next node or event scheduled. Figure 10 displays the time cost and adjacent node information from the "Searching" event in the *Longbow* network.

Longbow		Out				Connected to ...					
Node #	Name	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost
1	Searching	2	1.000	0.000	0.000	1	0.95	999999	27	0.05	3600

Figure 10. Node 1 from ***Longbow*** **Worksheet**

The next node is quickly found to be node one (0.95 > 0.058). The time associated with scheduling node one is "999999", indicating that this event is not to be scheduled on the

event list. In this particular case, "Searching" is not scheduled again because detections occur continuously throughout the simulation.

Run removes the current event from the top of the event list and sorts the remaining events by the time they are to occur. Figure 11 displays the updated event list.

Begin Time	Event	Sheet	Node	Param 1	Param 2	Param 3	Param 4
106.22	Friendly 1 Detects Group 5	Longbow	2		5		
114.55	Friendly 1 Detects Group 3	Longbow	2		3		
128.72	Friendly 1 Detects Group 1	Longbow	2		1		
150.67	At Waypoint	Longbow	28				
172.47	Friendly 1 UnDetects Group 1	Longbow	29		1		
178.11	Friendly 1 UnDetects Group 3	Longbow	29		3		
192.41	Friendly 1 UnDetects Group 5	Longbow	29		5		
924.35	Receiving Info	Info	1				
4188.88	Detected by Enemy	Detected	1				
30459.56	Malfunction	Malfunction	1				
999999.00	End						

Figure 11. *EventList* Worksheet (Time = 0.00; after *nextNode*)

Run then returns to the top of the event list to begin the next event: "Friendly 1 Detects Group 5". This event begins at 106.22, so *Run* calls the *move* subroutine to move all friendly and enemy entities. Their new positions reflect where they would be if they moved at the constant speed and in the constant direction assigned on the *Friendly* and *Enemy* worksheets for 106.22 seconds. This movement time is the time difference between the beginning of the previous event and the beginning of the current event. The *Friendly* and *Enemy* worksheets record the updated positions.

As before, *Run* determines if this specific node has associated subroutines. The code below shows that *Run* will call the subroutine *detection* then *clearDetect*.

```
Case "Longbow"
   Select Case atNode
      ...
      Case 2
        Call detection(ByVal time)
        Call clearDetect
```

The *detection* subroutine records all pertinent information concerning the detection: enemy identification number (from the "Param 2" column of the event list), time, location, and rate and direction of movement. The *DetectList* worksheet maintains this information as shown in Figure 12. *detection* also updates the *Enemy* worksheet, showing enemy group five has been detected. This is displayed in Figure 13.

enemy ID	Range	X	Y	Detected Speed	Direction	Time	Engaged	Bypass
5		1764.32	7294.96	3.51	3.73	106.22	N	

Figure 12. *Detected* Worksheet (Time = 106.22)

						Direction		Detected		Killed?						
ID #	Type Tgt	# Veh	X - Coord	Y- Coord	Speed	Radians	Degrees	at Range	Detected	1	2	3	4	5	6	7
1	IFV	3	03169	08570	3.479	1.793	103	2191	N	N	N	N	N	N	N	N
2	IFV	4	08207	12380	3.715	3.409	195	2721	N	N	N	N	N	N	N	N
3	IFV	5	02919	08036	3.738	1.788	102	2357	N	N	N	N	N	N	N	N
4	IFV	6	13821	12068	2.970	1.632	93	2666	N	N	N	N	N	N	N	N
5	**IFV**	**5**	**01764**	**07295**	**2.932**	**3.770**	**216**	**2736**	**Y**	**N**	**N**	**N**	**N**	**N**	**N**	**N**

Figure 13. *Enemy* Worksheet (Time = 106.22)

The fact that group five's speed and direction of movement are not the same on these two sheets is by design. This simulates the non-constant speed and direct of movement of the vehicles. The *Detected* worksheet maintains the *perceived* speed and direction of

movement, while the *Enemy* worksheet maintains the actual values. For further discussion, refer to "*detection*" in Appendix C.

Run calls the subroutine *clearDetect* next, removing all future detection events from the event list. This simulates the fact that the Longbow is currently busy and is not capable of detecting.

Run then calls *nextNode* to determine which event to schedule next. This time the random number drawn is 0.82. One can see from Figure 14 that the next event to schedule will be "Identifying (Neutral)", node five. The cumulative probability at that point is 0.90 (0.6 + 0.2 + 0.1). This event is scheduled to begin one second after the detection event occurred. The one second corresponds to the time elapsed between the realization that a detection occurred and the beginning of the identification process. In a Longbow, the detect-identify-prioritize process is automated and takes only a few seconds.

Longbow		Out				Connected to ...											
Node #	Name	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost
2	Target Detected	4	1.000	0.000	0.000	3	0.60	0.000	4	0.20	0.000	5	0.10	0.000	6	0.10	0.000
3	Identifying (Enemy)	1	1.000	0.000	0.000	7	1.00	0.000									
4	Identifying (Friendly)	1	1.000	0.000	0.000	1	1.00	999999									
5	Identifying (Neutral)	1	5.000	0.000	0.000	1	1.00	999999									
6	Identifying (Unknown)	4	5.000	0.000	0.000	3	0.30	0.000	4	0.20	0.000	5	0.45	0.000	6	0.05	0.000

Figure 14. *Longbow* Worksheet Excerpt

The updated event list is displayed in Figure 15. Notice that *clearDetect* did not remove the “un-detect” event for group 5. The Longbow is still focused on that group.

Begin Time	Event	Sheet	Node	Param 1	Param 2	Param 3	Param 4
107.22	Identifying (Neutral)	Longbow	5				
150.67	At Waypoint	Longbow	28				
192.41	Friendly 1 UnDetects Group 5	Longbow	29		5		
924.35	Receiving Info	Info	1				
4188.88	Detected by Enemy	Detected	1				
30459.56	Malfunction	Malfunction	1				
999999.00	End						

Figure 15. *EventList* Worksheet (Time = 107.22)

As before, *Run* acts upon the first event in the event list by first moving all entities (for 107.22 – 106.22 = 1.00 second). The "Identifying (Neutral)" event completes three actions before *Run* identifies the *nextNode*. First, the last detection entered on the *DetectList* sheet, now identified as a neutral target, is updated to indicate that it has been engaged ("Y") and no action has been taken ("Friend/Neutral" is placed in the last column). The event list is then cleared of all detection events (*clearDetect*) and new detections are scheduled (*schedDetect*). This event does not schedule a follow-on event. The updated event list is shown in Figure 16.

Begin Time	Event	Sheet	Node	Param 1	Param 2	Param 3	Param 4
114.55	Friendly 1 Detects Group 3	Longbow	2		3		
128.72	Friendly 1 Detects Group 1	Longbow	2		1		
150.67	At Waypoint	Longbow	28				
172.47	Friendly 1 UnDetects Group 1	Longbow	29		1		
178.11	Friendly 1 UnDetects Group 3	Longbow	29		3		
192.41	Friendly 1 UnDetects Group 5	Longbow	29		5		
924.35	Receiving Info	Info	1				
4188.88	Detected by Enemy	Detected	1				
30459.56	Malfunction	Malfunction	1				
999999.00	End						

Figure 16. *EventList* Worksheet (Time = 114.55)

Run proceeds in a similar manner for this detection event but this time the target group is identified as an enemy group. The "Identifying (Enemy)" event does not have any associated subroutines and the "Prioritizing" event is always the follow-on event ("Prob" = 1.00). The "Prioritizing" event calls the *Prioritize* subroutine to sort the detection list based on the target range from the Longbow. At this point only one "enemy" group is listed on the detection list so the Prioritize routine is inconsequential.

Determining the next node to schedule after "Prioritizing" is synonymous with deciding how to engage the target: call-for-fire, RFHO to an Apache, self-engage, or bypass. However, the process is not entirely random. If the Apache that would receive the RFHO or the artillery is currently engaging a target, the probabilities of these events being scheduled next would be set equal to zero on the *Longbow* network worksheet. *Run* repeats the "Prioritizing" event as often as necessary until a method of engagement is chosen. The "-1" cost associated with the last adjacent node, the node indicating to repeat the "Prioritizing" event, nullifies the one-second cost associated with occupying that node (Figure 17). This results in *Run* scheduling the "Prioritizing" event again at the same time.

Longbow Node #	Name	Out Degree	Cost	Par 1	Par 2	Connected to ... Node	Prob	Cost	Node	Prob	Cost
7	Prioritizing	5	1.000	0.000	0.000	8	0.15	0.000	9	0.70	0...
8	Deciding (Self Engage)	3	4.000	0.000	0.000	19	0.70	0.000	20	0.10	0...
9	Deciding (CFF)	1	4.000	0.000	0.000	15	1.00	0.000			
10	Deciding (RFHO)	1	4.000	0.000	0.000	12	1.00	0.000			
11	Deciding (Bypass)	1	4.000	0.000	0.000	1	1.00	999999			

Longbow (Con't) Node #	Name		Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost
7	Prioritizing	...	10	0.10	0.000	11	0.50	0.000	7	1.000	**-1.0**
8	Deciding (Self Engage)	...	21	0.20	0.000						

Figure 17. *Longbow* Worksheet Excerpt

In our example all options are available; but, the decision is made to bypass the target group. The "Bypass" event notes this on the *DetectList* worksheet by writing "Bypass" in the last column. Detection events are then cleared (*clearDetect*) and rescheduled (*schedDetect*). The resulting event list appears in Figure 18.

Begin Time	Event	Sheet	Node	Param 1	Param 2	Param 3	Param 4
128.72	Friendly 1 Detects Group 1	Longbow	2		1		
150.67	At Waypoint	Longbow	28				
172.47	Friendly 1 UnDetects Group 1	Longbow	29		1		
178.11	Friendly 1 UnDetects Group 3	Longbow	29		3		
192.41	Friendly 1 UnDetects Group 5	Longbow	29		5		
924.35	Receiving Info	Info	1				
4188.88	Detected by Enemy	Detected	1				
30459.56	Malfunction	Malfunction	1				
999999.00	End						

Figure 18. ***EventList*** **Worksheet (Time = 128.72)**

Run continues with the next event on the event list, the detection of Group 1. Following the same procedure as before, this group is identified as an enemy and the decision is made to engage with artillery resulting in a call-for-fire. The current detection list is displayed in Figure 19.

				Detected				
enemy ID	Range	X	Y	Speed	Direction	Time	Engaged	Bypass
5	7055.68	1764.32	7294.96	3.51	3.73	106.22	Y	Friend/Neutral
1	7950.70	3245.35	8552.38	2.79	1.77	128.72	N	
3	12471.87	2949.30	8029.63	3.84	1.79	114.55	Y	Bypass

Figure 19. ***DetectList*** **Worksheet (Time = 130.72)**

The "Decision (CFF)" event always schedules the "Preparing ATHS" event as the follow-on event. This event indicates the Longbow crew is beginning to manually

prepare the ATHS call-for-fire message. This event includes code to search the prioritized detection list for the identification number of the highest priority group not engaged and to record the specific detection information from the detection list for that group. In this example the group identified is Group 1.

Figure 20 shows the time to complete the "Preparing ATHS" task is a random observation from a Normal distribution having a mean of 40 seconds and a standard deviation of 5 seconds. The observed time was 39.17 seconds. "Sending to AFATDS" is always the follow-on event.

Longbow		Out				Connected to ...					
Node #	Name	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost
15	Preparing ATHS Msg	1	N	40.000	5.000	16	1.00	0.000			
16	Sending to AFATDS	2	7.000	0.000	0.000	18	0.90	0.000	17	0.10	0.000
17	AFATDS not rec'd	1	8.000	0.000	0.000	16	1.00	0.000			
18	AFATDS rec'd	1	1.000	0.000	0.000	Artillery	1.00	0.000			

Figure 20. ***Longbow*** **Worksheet Excerpt**

However, before this event occurs, the Longbow reaches its first waypoint, indicated by the "At Waypoint" event at the time 150.67. This event invokes the *atWayPoint* subroutine. *atWayPoint* adjusts the Longbow's course direction on the *Friendly* worksheet, schedules another "At Waypoint" event to coincide with the arrival at the next waypoint, moves the "X" on the Parameters worksheet marking the next waypoint, and clears and reschedules all detection events based upon the new course direction. The event list at this point is shown in Figure 21.

Begin Time	Event	Sheet	Node	Param 1	Param 2	Param 3	Param 4
174.89	Sending to AFATDS	Longbow	16				
187.38	Friendly 1 UnDetects Group 5	Longbow	29		5		
194.59	Friendly 1 UnDetects Group 3	Longbow	29		3		
198.91	Friendly 1 UnDetects Group 1	Longbow	29		1		
355.74	At Waypoint	Longbow	28				
924.35	Receiving Info	Info	1				
4188.88	Detected by Enemy	Detected	1				
30459.56	Malfunction	Malfunction	1				
999999.00	End						

Figure 21. ***EventList*** **Worksheet (Time = 174.89)**

The "Sending to AFATDS" event marks the beginning of action for the artillery, so the variable indicating whether or not the artillery is busy is now set to "true". This impacts future "Prioritizing" events as previously discussed. The next node for the "Sending to AFATDS" event either indicates that the message was not received and must be resent or that the message was received. Once the message is received, the next event scheduled is the first event on the "Artillery" worksheet. This worksheet is shown in Figure 22.

Artillery		Out				Connected to ...								
Node #	Receive CFF	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost
1	Analyzing Mission	1	5.000	0.000	0.000	2	1.000	0.000						
2	Sending to Guns	3	15.000	0.000	0.000	6	0.900	0.000	3	0.050	0.000	4	0.050	0.000
3	Sending Again	1	5.000	0.000	0.000	2	1.000	0.000						
4	Waiting for Cmd	1	N	30.000	5.000	5	1.000	0.000						
5	Cmd Rec'd	1	1.000	0.000	0.000	6	1.000	0.000						
6	Firing Rounds	2	TBD	0.000	3.000	7	0.010	0.000	8	0.990	0.000			
7	Miss Fired (1 tube)	1	1.000	0.000	0.000	8	1.000	0.000						
8	Rounds Impact	1	10.000	0.000	0.000	9	1.000	0.000						
9	End Artillery	1	0.000	0.000	0.000	1	1.000	999999						

Figure 22. ***Artillery*** **Worksheet**

There are no subroutines associated with the first five events on the *Artillery* worksheet. The "Firing Rounds" event accomplishes several tasks as shown by the following code:

```
Case "Artillery"
    Select Case atNode
        Case 6                  'Firing rounds
            numRnds = howManyRnds(artyEnID)   'determine how many rounds to fire
            Call setTimeOfFlt(detectX, detectY)  'determine the time of flight of the rnd
            artyBusy = False                          'artillery is no longer busy
            Sheets("Longbow").[K10].Value = 0.7       'artillery is again an option
```

The *setTimeOfFlt* subroutine replaces the "TBD" entry in the *Artillery* worksheet (Figure 22) with the actual time of flight of the rounds.

The simulation continues until the "Rounds Impact" event. This event calls two subroutines: *predictXY* and *shootArty*. The *predictXY* subroutine provides the predicted location of the lead vehicle in the target group based on the *detected* location, speed and direction of movement, and the time of detection. As a reminder, the detected speed and direction of movement are not the actual speed and direction of the group (refer to “detection” in Appendix C). The *shootArty* subroutine uses this predicted location to determine the aim points, and then simulates the appropriate number of rounds impacting. A more detailed discussion of this subroutine is in Appendix C. Vehicle kills are indicated on the *Enemy* worksheet. Figure 23 shows that the third vehicle in Group 1 was killed as a result of this engagement.

						Direction		Detected		Killed?						
ID #	Type Tgt	# Veh	X - Coord	Y- Coord	Speed	Radians	Degrees	at Range	Detected	1	2	3	4	5	6	7
1	IFV	3	03555	08482	3.479	1.793	103	2191	Y	N	N	Y	N	N	N	N
2	IFV	4	08095	11972	3.715	3.409	195	2721	N	N	N	N	N	N	N	N
3	IFV	5	03334	07945	3.738	1.788	102	2357	Y	N	N	N	N	N	N	N
4	IFV	6	14158	12048	2.970	1.632	93	2666	N	N	N	N	N	N	N	N
5	IFV	5	01568	07025	2.932	3.770	216	2736	Y	N	N	N	N	N	N	N

Figure 23. ***Enemy*** **Worksheet (Time = 229.89)**

Run continues to drive the simulation in the same manner until an "End of Mission" event occurs. This event calls the *endMission* subroutine that clears the event list and ends the simulation. The *Output* worksheet has captured the sequence of events executed because the "print" option was chosen on the *Menu* worksheet. Figure 24 shows the final result.

The *Stats* worksheet captures the number of vehicles engaged by artillery and the number of those killed for each artillery engagement. The top of the sheet (Figure 25) provides summary statistics of the data. The "# Veh" column refers to the total number of vehicles (not groups of vehicles) engaged with artillery. The "Killed" column contains the number of those vehicles that were killed. The four cells at the top of each column provide summary statistics for the entire run. The cells below these summary statistics contain the actual values for each engagement.

This example simulation run contained only one artillery engagement. The time required to complete one hundred such runs is less than four minutes on a computer with an Intel Pentium II processor operating at 333MHz.

The next chapter demonstrates how this model was modified to analyze the two call-for-fire procedures.

Sheet	Node	Name	Begin Times Sec	Min
Longbow	1	Searching	0.00	0.00
Longbow	2	Friendly 1 Detects Group 5	106.22	1.77
Longbow	5	Identifying (Neutral)	107.22	1.79
Longbow	2	Friendly 1 Detects Group 3	114.55	1.91
Longbow	3	Identifying (Enemy)	115.55	1.93
Longbow	7	Prioritizing	116.55	1.94
Longbow	11	Deciding (Bypass)	117.55	1.96
Longbow	2	Friendly 1 Detects Group 1	128.72	2.15
Longbow	3	Identifying (Enemy)	129.72	2.16
Longbow	7	Prioritizing	130.72	2.18
Longbow	9	Deciding (CFF)	131.72	2.20
Longbow	15	Preparing ATHS Msg	135.72	2.26
Longbow	28	At Waypoint	150.67	2.51
Longbow	16	Sending to AFATDS	174.89	2.91
Longbow	18	AFATDS rec'd	181.89	3.03
Artillery	1	Analyzing Mission	182.89	3.05
Longbow	29	Friendly 1 UnDetects Group 5	187.38	3.12
Artillery	2	Sending to Guns	187.89	3.13
Artillery	6	Firing Rounds at Enemy 1	192.89	3.21
Longbow	29	Friendly 1 UnDetects Group 3	194.59	3.24
Longbow	29	Friendly 1 UnDetects Group 1	198.91	3.32
Artillery	8	Rounds Impact	219.89	3.66
Artillery	9	End Artillery	229.89	3.83
Longbow	28	At Waypoint	355.74	5.93
Longbow	28	At Waypoint	527.38	8.79
Longbow	28	At Waypoint	678.05	11.30
Longbow	28	At Waypoint	917.92	15.30
Info	1	Receiving Info	924.35	15.41
Info	3	Rec'd Red S.A.	925.35	15.42
Longbow	28	At Waypoint	1026.60	17.11
Longbow	28	At Waypoint	1135.27	18.92
Longbow	30	End of Mission	1135.27	18.92

Figure 24. ***Output*** **Worksheet (End of Mission)**

	# Veh	Killed
mean	3.00	1.00
sd	0.00	0.00
max	3	1
min	3	0
	3	1

Figure 25. **Sample** ***Stats*** **Worksheet**

IV. ANALYSIS

A. PURPOSE AND PROBLEM REVISITED

As previously discussed, the purpose of this study is to demonstrate how a combat simulation model can be used to answer questions similar to the following:

> *Would a direct, digital link between a Longbow and a field artillery unit improve the ability of the field artillery to prosecute targets?*

Specifically, this study compares two Longbow call-for-fire procedures (the current ATHS procedure and the proposed RFHO procedure) by evaluating their impact on the combat effectiveness of an artillery unit. The appropriate measure of effectiveness for this comparison is the expected number of vehicles destroyed per engagement. The null and alternate hypotheses are as follows:

> H_o: The difference in expected number of kills obtained using the RFHO procedure is less than or equal to the expected number of kills obtained using the current ATHS procedure.
>
> H_1: The difference in expected number of kills obtained using the RFHO procedure is greater than the expected number of kills obtained using the current ATHS procedure.

While the author expects the difference to be greater than zero, the null hypothesis remains less than or equal to zero. This is primarily due to the fact that no one has a clear idea of how much more effective the RFHO procedure would be. In addition, this potentially provides a more powerful test result by requiring *significant* evidence of a

difference in order to conclude that the RFHO procedure is more effective. This is opposed to merely being able to draw the conclusion that significant evidence does not exist that proves the RFHO procedure is not more effective. (The double negative is required here.) Significant evidence is defined by the probability of observing the sample data if the null hypothesis is true. To reject the null hypothesis, the probability of observing the sample data must be below a specified threshold. This threshold is the accepted probability of rejecting the null hypothesis when it is, in fact, true (Type I error). For this study, significance is associated with a 95% confidence level; so, the probability of rejecting a null hypothesis when it is, in fact, true is 0.05. Obviously, failing to reject the null hypothesis has less stringent requirements. In most cases, the probability of failing to reject the null hypothesis when it is false (Type II error) is higher than the probability of committing a Type I error. Therefore, a more powerful test is one that requires significant evidence to prove the desired conclusion. In this study, significant evidence is required to prove that the RFHO procedure is superior to the ATHS procedure.

This is similar to our judicial system proving innocence or guilt. The null hypothesis used in our court system states that the defendant is innocent. The alternative hypothesis, requiring significant evidence for proof, is one of guilt. Society demands significant evidence of guilt before punishment is imposed. The probability of sentencing an innocent person (Type I error) must be lower than the probability of not sentencing a guilty person (Type II error).

B. DESIGN OF EXPERIMENT

This study incorporates a pre/post-process methodology to evaluate the hypothesized differences between the two call-for-fire procedures. Each artillery engagement consists of two trials. The first trial simulates an engagement with the Longbow utilizing the current ATHS procedure. For the second trial, the target group is set back to its original state and the engagement is repeated with the Longbow utilizing the hypothesized RFHO procedure. These two trials comprise one engagement replication and provide a matched pair of values indicating the numbers of vehicles killed utilizing each procedure under identical conditions. This matched pair provides one observation of the difference in the number of vehicles killed. A simulation "run" consists of 2,000 engagement replications.

After validating the model (discussed in Section D of this chapter), a base case evaluation is completed. This base case represents the author's estimate of the current ATHS procedure and the RFHO procedure and is used to determine if one procedure is better to the other. The key parameters used in the base case are the mean time required to prepare the ATHS message and the lethal area. Lethal area is a parameter used to define the effectiveness of a specific type of munition (artillery round) against a specific target. A lower lethal area implies that the round must impact closer to the target to obtain the same probability of kill as a round fired at the same target with a higher lethal area. Higher lethal area equates to more lethal effects based on the distance between the target and the point of the impact. The time to prepare the ATHS call-for-fire in the base case is a random observation from a Normal distribution with a mean of 40 seconds and a standard deviation of 5 seconds (hereafter noted as N (40,5)). These values are based on

the author's professional judgement and were deemed reasonable by analysts at Boeing (manufacturers of the Longbow). The lethal area is set at eight square meters, again based on the author's judgement. The base case consists of one run (2,000 replications)

After evaluating the base case, several excursions are evaluated to determine the sensitivity of the results to the two key parameters: time required to prepare the ATHS message and the lethal area. Excursions for ATHS message preparation times include two different mean values for the Normal distribution: 20 seconds and 60 seconds. The standard deviation of the preparation time is not changed. These specific mean values were chosen to reduce the probability of drawing the same preparation times during different excursions. The probability of drawing the same values from these different distributions is approximately 0.003. Lethal area excursions include values of 6 m^2 and 10 m^2. These values were chosen arbitrarily and have no relationship to any particular weapon system or target type. One simulation run (2,000 replication cycles) is completed for each combination of these values, resulting in eight additional runs.

C. MODEL MODIFICATIONS

1. General

The basic simulation presented in the previous chapter models the Longbow conducting a combat mission under its current configuration. Several modifications are required to coincide with the design of the experiment. An accurate comparison demands the elimination, or at least a reduction, of all external influences and sources of randomness within each replication. Target group size, direction and rate of movement,

range from the artillery unit, and all user-defined parameters must be held constant during each replication cycle. With this accomplished, any differences result strictly from the differences within the call-for-fire procedures.

To accomplish this, several features of the model are disabled. Random events that do not pertain to the objective of this study are eliminated: aircraft malfunctions, receipts of information, and all forms of engagement other than the call-for-fire. Target detection is simplified to provide immediate detection at the start of each replication, and the initial target group position is set within range of the artillery in order to reach steady-state as quickly as possible. Each replication ends immediately after the RFHO engagement to decrease the run time.

Within the model, the target group's movement state (speed, direction, time, and location) is recorded during the "detection" event and the time is noted at the beginning of the "Preparing ATHS" event. This latter event is the first time a difference due to the call-for-fire procedures could occur. After the artillery engagement is completed utilizing the ATHS procedure, the target group is reset to the recorded state and the engagement is repeated utilizing the RFHO procedure, completing one replication cycle. The same stream of random numbers is used during each trial within a replication to ensure ballistic errors do not influence the results. Different random streams are used for each replication. The model captures the number of vehicles killed for each procedure during an engagement on the *Stats* worksheet.

Several factors are allowed to vary between engagement replications: the initial target group location, target group speed, target group direction of movement, and ballistic errors of the artillery rounds. Additionally, the effect of each artillery round is a

Monte Carlo draw against a Gaussian lethality function. By not restricting these factors to specific values, the results of this study are more representative of all possible artillery engagement scenarios. Target group size and vehicle dispersion within the group are not allowed to vary. All target groups consist of four vehicles and their dispersion is defined on the *Parameters* worksheet. Although reducing the generality of the results, this eliminates the influence of the number of rounds fired and aim point choices (volley pattern).

2. Networks And Worksheets

The necessary modifications result in the addition of one new network (*Longbow2*) and one additional worksheet (*temp*). The *Longbow2* network is identical to the *Longbow* network described in the last chapter except for the one entry that simulates the new procedure. The *Longbow2* network replaces the "Preparing ATHS Msg" event with the "Preparing RFHO" event as shown in Figure 26. As previously stated, the time required to prepare the ATHS message call-for-fire is based upon the author's professional judgement and past experience in Apache-equipped attack helicopter battalions and is supported by personnel at Boeing. The actual value would be subject to numerous factors such as combat intensity and aircrew proficiency. The time required to prepare the RFHO is based on common sense: the copilot/gunner merely presses two buttons to send the RFHO. This value would be much less sensitive to external factors. No attempt is made to validate these values other than the verbal agreement with Boeing personnel.

Longbow Node #	Name	Out Degree	Cost	Par 1	Par 2	Connected to ... Node	Prob	Cost	Node	Prob	Cost
14	Call AH rec'd	1	0.000	0.000	0.000	10	1.000	0.000			
15	**Preparing ATHS Msg**	1	**N**	**40.000**	**5.000**	16	1.000	0.000			
16	Sending to AFATDS	2	7.000	0.000	0.000	18	1.000	0.000	17	0.000	0.000
17	AFATDS not rec'd	1	8.000	0.000	0.000	15	1.000	10.000			
18	AFATDS rec'd	2	1.000	0.000	0.000	Arty	1.000	0.000	19	0.000	0.000

Longbow2 Node #	Name	Out Degree	Cost	Par 1	Par 2	Connected to ... Node	Prob	Cost	Node	Prob	Cost
14	Call AH rec'd	1	0.000	0.000	0.000	10	1.000	0.000			
15	**Preparing RFO**	1	**U**	**1.000**	**2.000**	16	1.000	0.000			
16	Sending to AFATDS	2	7.000	0.000	0.000	18	1.000	0.000	17	0.000	0.000
17	AFATDS not rec'd	1	8.000	0.000	0.000	15	1.000	10.000			
18	AFATDS rec'd	2	1.000	0.000	0.000	Arty	1.000	0.000	19	0.000	0.000

Figure 26. Difference Between *Longbow* and *Longbow2* Networks

The *Temp* worksheet is a separate event list used to record the events from the *Longbow2* network as the artillery engagement was repeated. This allows the original event list to remain intact. The format of this sheet is identical to the *EventList* worksheet displayed in Appendix B.

3. Subroutines

Model modifications also resulted in the addition of three subroutines: *Linked*, *resetKills*, and *SortTempList*. *Run* calls the *Linked* subroutine during the "Evaluating BDA" event in the *Artillery* network to link the results of the two trials during one replication. The number of kills for the first (ATHS) trial is recorded, then *Linked* repeats the engagement using the *Longbow2* network to evaluate the RFHO kills. The modified code within *Run* is as follows:

```
Case 9      'evaluate BDA
   kill1 = countKills(enID)
   Call linked(enID, numRnds, markTime, detectSpeed, detectDir, _
      detectTime, detectX, detectY, tlex, tley, seed)
   kill2 = countKills(enID)
```

A more detailed description of the *Linked* subroutine is provided in Appendix C. The *resetKills* subroutine simply resets those vehicles killed during the ATHS engagement. The *SortTempList* subroutine sorts the events on the *Temp* worksheet based on time of occurrence. This subroutine is identical to the *SortEventList* subroutine.

D. MODEL VERIFICATION AND VALIDATION

Verification and validation (V&V) ensure a simulation model works as designed and provides reasonable results, respectively. Verification includes logical and mathematical verification and program verification. The former ensures that algorithms match their intended use and do not contain logic or mathematical errors. The latter ensures the algorithms have been correctly implemented in the program code. Validation is the process of comparing the model with the "real world" phenomena that it represents and subjectively defining an appropriate confidence level. There are three types of validity: descriptive validity, structural validity, and predictive validity. Descriptive validity measures the degree of confidence to which the model explains phenomena or presents information. Structural validity assesses the proper implementation of objects, variables, and processes. Predictive validity measures the degree to which the model can predict desired features of system behavior.

[Ref 11, p. VI-3 – VI-5].

V&V is a time consuming process, and some may say that complete V&V is an unreachable ideal. While verifying the simple model presented here is not extremely difficult, thoroughly validating the model would require extensive effort. For example, accurately assessing the predictive validity would require operational field testing and evaluation, under realistic combat conditions, of the systems involved. Obviously the results of such testing are not available and conducting such testing is clearly unreasonable.

Because this model is developed for demonstration purposes, only cursory effort was spent on verification and validation. Logical and mathematical verification and program verification were continuously assured during the development of this model by the author and advisors. Likewise, a high degree of confidence is associated with the descriptive and structural validity. To evaluate the predictive validity of the model, three runs were completed to determine if the model results matched the true expected results. This was accomplished by using the same message preparation times for both ATHS and RFHO calls-for-fire (a constant 1.5 seconds) and completing one run for each lethal area used in the study: 6, 8, and 10 m^2. A properly working model should result in no differences in the number of vehicles killed between the two call-for-fire procedures since the only possible difference (preparation time) has been eliminated. After 2,000 replications for each lethal area, there were no observed differences, as expected. Thus, the model was deemed appropriate for demonstration purposes. Independent V&V should be conducted if this model is used for purposes other than demonstration.

E. COMPARISON OF CALL-FOR-FIRE PROCEDURES (BASE CASE)

1. Approach

Statistical analysis comparing the mean values of two populations with unknown or known but unequal variances is usually accomplished using the *t*-test. A special case of the *t*-test occurs when data are collected in pairs, as in this study. The results of each pair of trials are taken under identical conditions, but these conditions will not be exactly the same between all replications. As mentioned, several sources of randomness between replications are not removed from the simulation: initial target location, speed, and direction of movement, and ballistic error of the artillery rounds. The test procedure for this type of analysis is to evaluate the *difference* between the observations of each replication. This reduces the overall variability between each replication resulting in a more powerful test. This procedure is called the *paired* *t*-test.

As with the standard *t*-test, the paired *t*-test assumes the underlying distributions of the sample populations and the observed differences are Normally distributed [Ref 12, p. 291]. The population distributions and the observed differences in this study, however, are neither continuous nor Normally distributed. Only five possible values for the number of vehicles killed are possible (0, 1, 2, 3, or 4) and nine possible values for the differences observed. These data are highly discrete and not Normal for the number of vehicles killed.

However, the paired *t*-test can be applied if the underlying data can be evaluated as Normal using the Central Limit Theorem. This theorem states

If $X_1, X_2, \ldots, X_n$ is a sequence of n independent random variables with $E[X_i] = \mu_i$ and $Var[X_i] = \sigma^2$ (both finite) and $Y = X_1+X_2+\ldots+X_n$ then

$$Z_n = \frac{Y - \sum_{i=1}^{n} \mu_i}{\sqrt{\sum_{i=1}^{n} \sigma_i^2}}$$

has an approximate Normal (0,1) distribution as n approaches infinity.[Ref. 11, p. 182].

The required conditions for this assumption are that individual observations make a negligible contribution to the variance of the sum and that no single observation makes a significant contribution to the sum. This is true regardless of the variable's frequency distribution. Considering the large number of replications conducted in this study (2,000 per run), assuming these conditions are met is reasonable. Therefore, the paired *t*-test is used to evaluate the differences between the expected number of vehicles killed.

2. Method

One simulation run was completed to provide 2,000 observed differences, as previously discussed. Using a personal computer with an Intel Pentium II processor operating at 333MHz, this run was completed in approximately twenty minutes.

3. Output

Table 1 summarizes the simulation output from the base case run. The top two rows show the total number of observations for each possible number of vehicles killed. There can never be a negative number of vehicles killed, so these values are "N/A". The differences displayed in the bottom row represent the number of vehicles killed

(RFHO, or post-process) minus the number of vehicles killed (ATHS, or pre-process). These differences do not represent the differences between the rows of the table.

	Observed # Vehicles Killed and Observed Differences						
	-2	-1	0	1	2	3	Total
ATHS	N/A	N/A	1216	673	109	2	2000
RFHO	N/A	N/A	1076	775	147	2	2000
Differences	24	211	1366	362	36	1	2000

Table 1. Summary of Base Case Simulation

While the distributions for the number of vehicles killed are not Normal for the ATHS and RFHO samples, Figure 27 shows the differences do have a Normal shape, as expected based on the Central Limit Theorem.

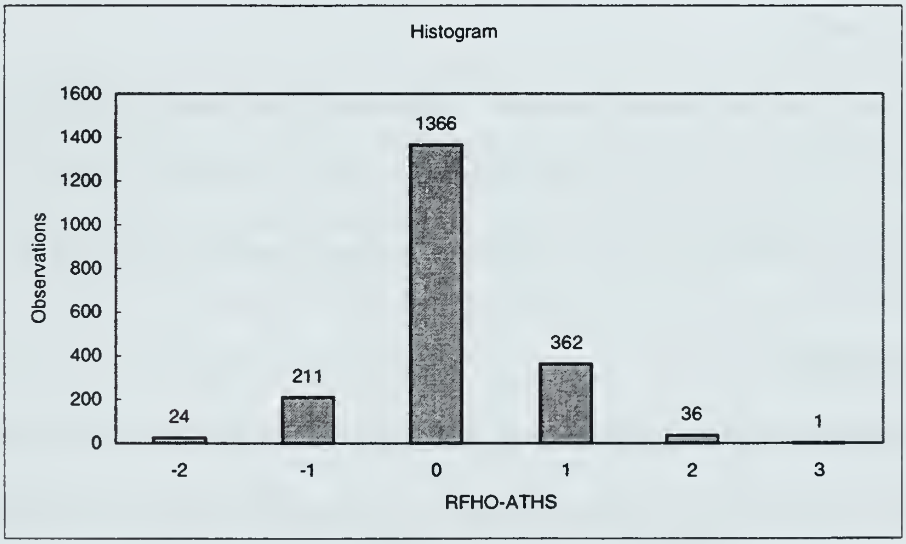

Figure 27. Observed Differences in Base Case

4. Hypothesis Testing

As discussed, the paired *t*-test evaluates the differences between paired observations. If D_i represents the difference between the observed number of kills (RFHO – ATHS) in the i^{th} observed pair, and all D_i are assumed to be independent and identically distributed random variables that follow a Normal distribution with mean μ_D and variance σ^2_D, then the hypotheses for the one-tailed, paired *t*-test can be written as follows:

$$H_o: \mu_D \leq \Delta_o$$
$$H_1: \mu_D > \Delta_o$$

Δ_o represents the value of the tested difference. In this study, Δ_o equals zero because we are testing against a null hypothesis that states the proposed RFHO procedure is not superior to the current ATHS procedure.

The statistical analysis program S-Plus was used to determine the value of the test statistic *t*. The results of this analysis are shown below:

```
                    Paired t-Test

data:  x: baseRFHO , and y: baseATHS
t = 6.2676, df = 1999, p-value = 0
alternative hypothesis: true mean of differences is greater than
0
95 percent confidence interval: 0.06563223  NA
sample estimates: mean of x - y = 0.089
```

The p-value of 0 indicates the null hypothesis is rejected at the 0.05 significance level. There is sufficient evidence to conclude that the true difference between these means is not less than or equal to 0.

The results of the base case indicate that the RFHO system does increase the effectiveness of the artillery unit under the given assumptions. The average number of

vehicles killed per engagement using the ATHS procedure was 0.45; using the RFHO procedure it was 0.54. While this may not seem significant, this difference represents a 20% increase in artillery effectiveness. On the average, for every twelve artillery engagements against a group of four moving vehicles, employing the RFHO procedure instead of the ATHS procedure would result in one additional vehicle kill.

F. SENSITIVITY ANALYSIS

1. General

Sensitivity analysis of input parameters is an important step in analysis that relies on simulation. Two of the most important parameters used in this study are the time required to prepare the ATHS call-for-fire message and the lethal area of the artillery round against the target vehicles. Therefore, sensitivity analysis is conducted to determine if the observed differences were sensitive to these parameters.

2. Approach

Analyzing the effect caused by different levels of two different factors (preparation time and lethal area) constitutes a two-factor, factorial experiment. The appropriate procedure for testing for differences caused by these effects is two-way analysis of variance (ANOVA).

ANOVA assumes all effects caused by different factors are additive. Observed values are then modeled as a linear combination of the population mean and the different factors. The linear model associated with ANOVA can be written as follows:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_{ij} + \varepsilon_{ijk}$$

- y_{ijk} represents the k^{th} observation (an observed difference) under preparation time i and lethal area j.
- μ represents the overall mean of the differences under all conditions.
- α_i represents the treatment effect caused by preparation time i.
- β_j represents the treatment effect caused by lethal area j.
- γ_{ij} represents the interaction effect caused by both factors.
- ε_{ijk} represents the random error for observation ijk attributed to the experiment (assumed to have constant variance).

In this study both factors have three levels. ATHS preparation time levels consist of three Normal distributions: N (20, 5), N (40, 5), and N (60, 5) all in units of seconds. The three lethal area levels are 6, 8, and 10 meters^2. The fact that these values were not chosen randomly results in a *fixed effects* ANOVA model.

3. Method

One simulation run (2,000 replications) was completed for each combination of the factor levels resulting in eight more simulation runs. The resulting data set for this analysis consists of 18,000 observed differences (base case and excursion runs). The total time for all runs was four hours on a personal computer with an Intel Pentium II processor operating at 333MHz.

4. Output

Table 2 displays the mean differences for each simulation run. These values are the sample means (differences) of 2,000 replications for each combination of factors.

		Mean VMF Prep Time		
		20	40	60
Lethal Area	6	0.0225	0.0455	0.0955
	8	0.0535	0.0890	0.1340
	10	0.0810	0.1595	0.2095

Table 2. Mean Differences Observed

Figure 28 displays a three-dimensional plot for these results and the validation results, illustrating the mean differences for each combination of factors. This chart clearly shows that the RFHO procedure is superior at all times greater than 1.5 seconds (the validation run). Appendix D contains a more detailed presentation of the observed values.

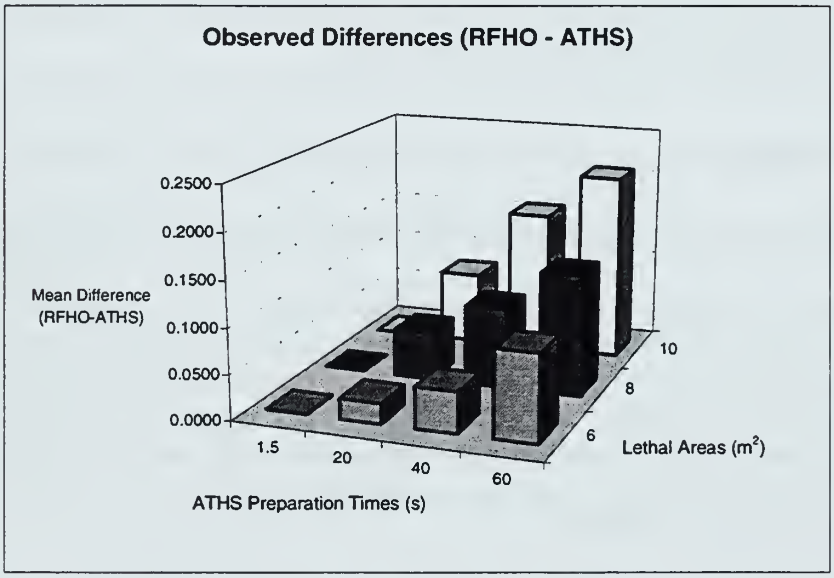

Figure 28. Mean Differences Observed

Figures 29 and 30 provide the interaction plots for these data. The validation results are also presented in these plots as a reference. The points associated with the

validation data represent the differences observed if the call-for-fire preparation times were the same. As discussed, there were no differences, so all values are zero.

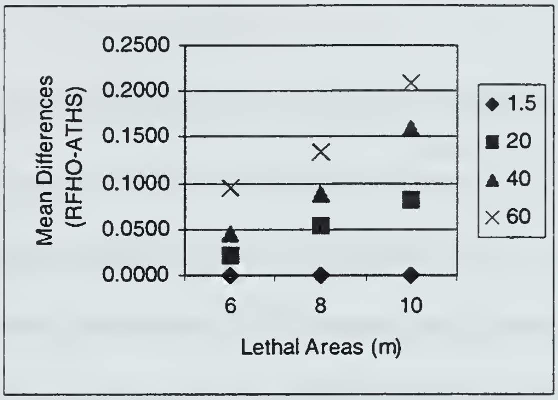

Figure 29. Interaction (Lethal Area)

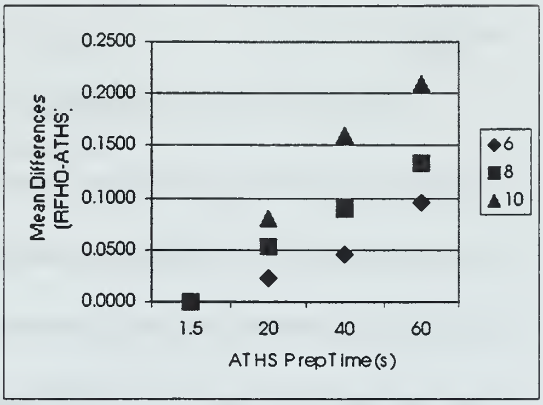

Figure 30. Interaction (Prep Time)

Both interaction plots suggest that the specific choices for ATHS preparation times and lethal areas affect the observed differences. This is indicated by the fact that the points in the plots do not lie along horizontal lines. The diamonds (◊) in Figure 29 (corresponding to an ATHS preparation time of 1.5 seconds) provide an example of a case when lethal area does not affect the differences. These points lie along a horizontal line, indicating that the results (differences) are the same regardless of the lethal area. In Figure 30, all the points associated with the 1.5-second preparation time lie on top of each other.

These plots also suggest possible interaction effects as the preparation time changes from 20 to 40 seconds. This is indicated by the increasing vertical distances between points as lethal area increases (Figure 29) and as preparation time increases (Figure 30). Increasing the time preparing the ATHS message while engaging softer targets (or using more lethal munitions) results in a greater difference between the two

procedures than if just one of these factors was changed. The opposite also holds true. This may indicate a decreased significance of lethal areas when preparation time is 20 seconds.

In general, these plots suggest using the RFHO procedure when engaging "softer" targets or when using more lethal munitions (both indicated by higher lethal areas) results in increasingly more vehicle kills than if the ATHS procedure was used. Similarly, using the RFHO procedure results in increasingly more kills than the ATHS procedure as the time required to prepare the ATHS message increases. The difference in the results of these two procedures decreases as the ATHS preparation decreases. However, the reader is cautioned that in fixed effects analysis such as this, statistical analysis only applies to the specific values presented. Generalizations and interpolations or extrapolations of the data are not necessarily valid.

5. Hypothesis Testing

These observations can be verified through ANOVA. Using the linear model previously addressed,

$$y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_{ij} + \varepsilon_{ijk}$$

the appropriate hypotheses for a two-way, fixed-effects ANOVA are written as follows:

$$
\begin{array}{lcl}
H_0\text{: } \alpha_i = 0 & \text{vs.} & H_1\text{: } \alpha_i \neq 0 \\
H_0\text{: } \beta_j = 0 & \text{vs.} & H_1\text{: } \beta_j \neq 0 \\
H_0\text{: } \gamma_{ij} = 0 & \text{vs.} & H_1\text{: } \gamma_{ij} \neq 0
\end{array}
$$

These null hypotheses imply that the specified levels of ATHS preparation time and the lethal area and the interaction of these two factors do not effect the observed differences.

Table 3 displays the ANOVA results obtained using S-Plus.

	Df	Sum of Sq	Mean Sq	F Value	Pr(F)
Lethal Area	2	27.767	13.88372	38.72983	0
ATHS Prep Time	2	26.515	13.25756	36.98309	0
Interaction	4	2.350	0.58756	1.63904	0.1613
Residuals	17991	6449.345	0.35848		

Table 3. ANOVA Results

The low Pr(F) values in the right column indicate that two of the three null hypotheses are rejected at the 0.05 level of significance: lethal area effects and preparation time effects. There is not significant evidence of interaction.

However, these conclusions are only valid if the assumption that the experimental error values (ε_{ijk}'s) have a constant variance is reasonable. Assumptions concerning constant variance are frequently verified by examining plots of the residuals. Figure 31 displays a plot of the residual values versus the fitted values from the ANOVA model.

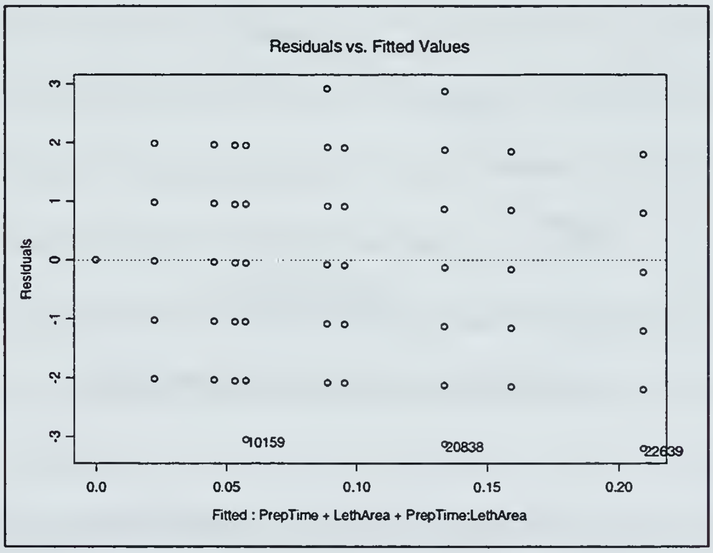

Figure 31. Residuals vs. Fitted Values (ANOVA)

A uniform, vertical dispersion of values in this plot would indicate constant variance. Unfortunately, the discrete nature of the data results in numerous residuals being plotted on top of each other, preventing a completely accurate inspection of the variance.

However, the Normal quantile-quantile plot in Figure 32 does support the assumption that the variance of residuals is constant. The discrete nature of the observed differences has resulted in a discrete set of fitted values. The relatively uniform, vertical spread of the residuals at these fitted values, coupled with the plot of residuals versus fitted values in Figure 31, suggest variance is constant. This is a rather crude but sufficient assessment.

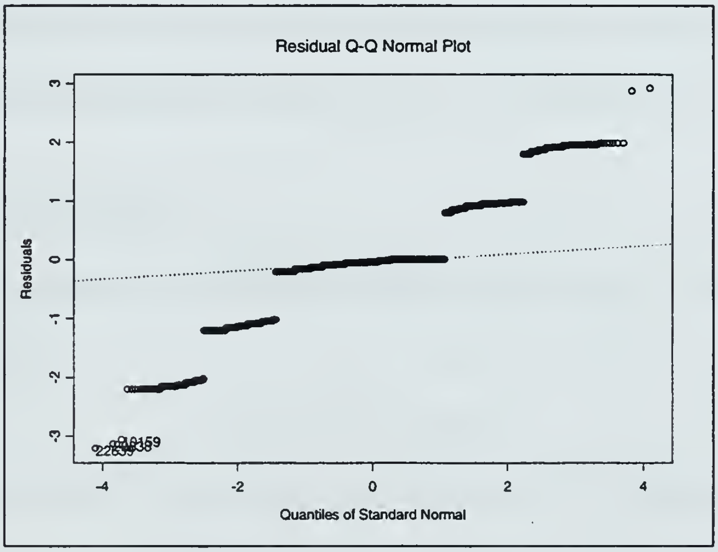

Figure 32. Normal Q-Q Residual Plot

Therefore, statistical analysis supports the hypothesis that specific values chosen for lethal area and ATHS preparation time affect the observed differences between the two call-for-fire procedures. Although ANOVA only leads to conclusions stating that

effects exist or do not exist, the previous plots certainly indicate that increasing either value results in greater differences, favoring the RFHO procedure.

These conclusions may be interpreted in several ways. The obvious interpretations are that aircrews would increase the effectiveness of artillery engaging moving targets if they could reduce the time required to prepare the ATHS call-for-fire, and the artillery would increase its own effectiveness if it used "better" munitions (indicated by higher lethal areas). Additionally, the particular combinations of lethal areas and preparation times appear to influence the results, although there is not sufficient evidence to support this hypothesis ($p = 0.16$). These observations lead to an interesting, albeit dangerous, generalization about "smart" munitions.

If smart munitions, such as Sense And Destroy Armor (SADARM) artillery rounds, can be crudely modeled as conventional artillery rounds with large lethal areas, then this study suggests that even these high-cost munitions may not make the effects of the current ATHS procedure comparable to the RFHO procedure. On the contrary, the RFHO procedure would further amplify their effects. This is perhaps best illustrated in Figure 33, which displays the percent increase in effectiveness resulting from the use of the RFHO procedure instead of the ATHS procedure.

In terms of relative increased effectiveness (percent increase in kills), the RFHO procedure showed little change between the lethal areas evaluated. If better munitions brought the level of effectiveness of the ATHS procedure to that of the RFHO procedure, the relative increases would approach zero for the larger lethal areas. This clearly is not the case. Although generalizations from fixed effects analysis are not recommended, as mentioned before, this observation is no less interesting.

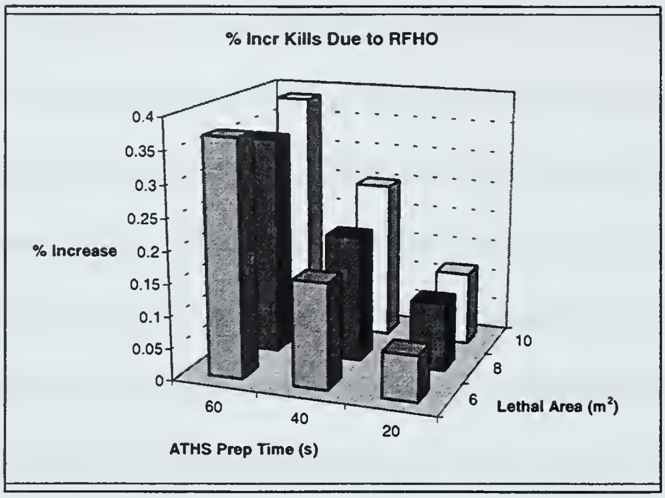

Figure 33. % Increase Kills Due to RFHO

Perhaps more importantly, Figure 33 emphasizes the fact that reducing the time required to prepare a call-for-fire can pay large dividends. Better munitions may increase effectiveness; but, the timeliness of targeting information appears to have a greater effect. For a Longbow aircrew, the RFHO procedure should be the standard.

G. SUMMARY

This chapter demonstrates a methodology to evaluate a difference in combat effectiveness for two particular combat systems through the use of simulation. This methodology incorporated a pre/post-process experimental design to collect paired observations. The paired *t*-test then led to the rejection of the hypothesis that the RFHO procedure was less than or equal to the current ATHS procedure in terms of numbers of vehicles killed. Two-way, fixed effects ANOVA further concluded that the observed differences were sensitive to specific lethal area values and times to prepare the ATHS messages. Graphic portrayal of these effects showed that the observed differences were greater for the larger lethal areas and ATHS preparation times selected.

V. RECOMMENDATIONS

A. GENERAL

The demonstration model developed in this study is designed to serve as a basis for additional analysis involving the Longbow. The comparison of the call-for-fire procedures serves as an example of how this model can be modified to answer a specific question and demonstrates the experimental design and statistical analysis required. The format for this experimental design and analysis can be applied to numerous other areas of study. This chapter discusses several general areas within the model that warrant further development and provides ideas for topics of further study.

B. MODEL IMPROVEMENT

Because this model is designed to serve as a basis for further analysis, the list of possible improvements is endless. The areas described below represent some of the major improvements that would be beneficial to many areas of interest.

1. Longbow Teams

This model provides two ways for tracking Longbows: as individual aircraft operating independently or as a group, tracking only the lead aircraft. The trend for future Longbow operations appears to be headed toward operating in teams of three or four aircraft. However, unlike past attack helicopter TTP's that measure the distance between aircraft in terms of "rotor discs", future Longbow TTP's may measure this distance in kilometers. This greatly increases the team's ability to detect the enemy and may increase the team's vulnerability. Unfortunately, modeling such a team as a group is unreasonable

and modeling each aircraft as an independent entity fails to account for the benefits of operating as a team.

2. Logistics

The lethality and maneuverability of the Longbow make it a valuable asset to commanders at all levels. Its absence from the battlefield is wasted potential. Yet the Longbow does not have an endless supply of ammunition or fuel, and rearming and refueling is a time consuming process. To accurately portray the overall combat effectiveness of this system, logistical concerns must be addressed. The model developed in this study provides a very poor representation of logistical issues. Further development in terms of fuel and ammunition consumption and aircraft reliability, availability, and maintainability (RAM) would be extremely beneficial and insightful.

3. Survivability

The Longbow has numerous forms of Aircraft Survivability Equipment (ASE) and sensors to enhance its survivability. This model provides a cursory representation of some of this equipment and does not include any of the sensors. Development in this area is a necessity if this model is used in a force-on-force scenario.

4. Weapons Effects

The use of simple probabilities of hit and probabilities of kill is usually sufficient for modeling engagements of a Hellfire missile (either laser-guided or millimeter-wave). However, accurate modeling of the effects of the Longbow's 2.75" rockets and 30mm

cannon requires a more rigorous approach. The model in this study uses probabilities of kill for all weapon systems.

5. Detections

To model detections of vehicles, this model uses a random range at which the vehicle is guaranteed to be detected by a Longbow. This random range is an implicit representation of environmental effects, aircraft capabilities, and detection TTP's. The actual detection process is extremely detailed and complex. This model would benefit by explicitly incorporating the capabilities of the millimeter-wave radar and the Forward Looking Infrared (FLIR) sight along with associated search and detection algorithms. Development in this area would facilitate the analysis of detection TTP's.

C. TOPICS OF FURTHER STUDY

While conducting this study, several topics worthy of additional study were identified. The following list identifies several of these topics.

1. The Impact of Information

As discussed in the Background section of this paper, future combat operations will be characterized by the rapid flow of battlefield information. The model presented in this study facilitates modeling a Longbow receiving information of all types. The methodology and analysis demonstrated provide an example of evaluating the impact of timely targeting information on field artillery effectiveness. Future study of other types of information (present position, logistical status, etc.) and other characteristics of information (reliability, quantity, relevance, etc.) would be insightful.

2. "Smart" Munitions

This study demonstrates the effectiveness of an artillery unit firing "dumb" munitions. In reality, future artillery units are more likely to engage moving targets with smart munitions. The experimental design and analysis demonstrated could easily be repeated for smart artillery munitions. The pre/post-process design is well suited for such analysis.

3. Search Strategies

As previously mentioned, the Longbow is not likely to continuously search the battlefield for targets. What is an optimal search technique that will maximize the probability of detecting targets and minimize the probability of being detected? Again, the pre/post-process design may be useful. After the Longbow searches a "battlefield" using some current procedure, the search is repeated under identical conditions using a hypothesized search pattern or mode. Similar analysis could result in evaluating the effectiveness of the searches.

4. Volley Pattern

The model developed in this study provides aim points for the artillery unit based on relative positions from the lead target vehicle. However, if the Longbow is capable of passing the exact locations of all vehicles in a group, should the artillery use all those locations for aim points or should they aim according to a specific pattern? Minor modifications to the current model using the pre/post-process design could quickly provide a first look.

VI. SUMMARY

This thesis has demonstrated the development and use of a simple, single-purpose simulation model. The model was developed on a personal computer using Microsoft Excel and was designed to answer a specific question:

> *Would a direct, digital communications link between sensor A and weapon system B improve the ability of weapon system B to prosecute targets?*

To demonstrate the use of this model, a comparative analysis was performed to evaluate two field artillery "call-for-fire" procedures: the current ATHS procedure and a proposed RFHO, digital procedure. The experiment incorporated a pre/post-process design resulting in paired observations of the artillery's effectiveness before and after incorporation of the new technology. The paired t-test led to the rejection of the hypothesis that the RFHO procedure was equal to the current ATHS procedure in terms of numbers of vehicles killed. Incorporating the RFHO procedure would increase the effectiveness of the field artillery. Two-way, fixed-effects ANOVA further concluded that the observed differences were sensitive to specific lethal area values and times to prepare the ATHS messages. Decreasing the time required to prepare the ATHS message and using better artillery munitions both resulted in increases in artillery effectiveness.

The thesis serves as a demonstration of a methodology for answering a complex question through the use of simple simulation. The model developed was designed to serve as a basis for follow-on studies involving the Longbow Apache. Recommendations for model improvement and examples of follow-on studies have been provided.

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APPENDIX A. NETWORK WORKSHEETS

This appendix displays the eight networks used in this study: *Longbow*, *Longbow2*, *Artillery*, *Apache*, *FARP*, *Malfunction*, *Detected*, and *Info*. All networks have been created using the network template shown in Figure A-1. As a reminder, all nodes represent the beginning of specific events.

Template		Out				Connected to ...					
Node #	Name	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost

Figure A-1. Network Template

The upper left cell displays the name of the network ("Template"). Each row in the network corresponds to a specific event. An explanation of each column in the template follows:

- *Node #* - The number of the node corresponding to the event listed in the row.
- *Name* – The name of the specific event. This name is displayed on the event list and, if the print option is chosen, on the *Output* sheet.
- *Out Degree* – The number of adjacent nodes.
- *Cost* – The amount of time consumed (in seconds) conducting this event. This entry may contain the letter "U", "N", "E", or "W" indicating that this time is a random observation from a uniform, normal, exponential, or Weibull distribution.

- *Par 1* – If the cost is a random observation, this entry indicates the first parameter used to identify the distribution. For a Uniform distribution, this value is the lower bound; for a normal distribution, this value is the mean; for an exponential distribution, this value represents the rate λ; and for a Weibull distribution, this value represents α. If the cost is not random, the entry is 0.
- *Par 2* – If the cost is a random observation, this entry indicates the second parameter used to identify the distribution. For a uniform distribution, this value is the upper bound; for a normal distribution, this value is the standard deviation; and for a Weibull distribution, this value represents β. Otherwise, the entry is 0.

The remaining columns are used to determine which event to schedule next. The *nextNode* subroutine draws a random observation from a Uniform (0,1) distribution and cycles through the "Prob" columns, adding each probability, until the cumulative total exceeds the observed random value. The Node-Prob-Cost pattern is repeated for each adjacent node.

- Node – The number of an adjacent node. A network sheet name may also appear here, indicating that the adjacent node is the first node on the specified worksheet.
- Prob – The probability of this node (or network) being scheduled next.
- Cost – If not equal to zero, this cost (time) represents a correction to be applied to the node cost. Values of "999999" are used when no additional

event is to be scheduled. The *Run* subroutine will not add an event to the event list if this value is greater than 999998.

Longbow Node #	Name	Out Degree	Cost	Par 1	Par 2	Connected to ... Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost
1	Searching	2	1.000	0.000	0.000	1	0.95	999999	27	0.05	3600									
2	Target Detected	4	1.000	0.000	0.000	3	0.60	0.000	4	0.20	0.000	5	0.10	0.000	6	0.10	0.000			
3	Identifying (Enemy)	1	1.000	0.000	0.000	7	1.00	0.000												
4	Identifying (Friendly)	1	1.000	0.000	0.000	1	1.00	0.000												
5	Identifying (Neutral)	1	1.000	0.000	0.000	1	1.00	0.000												
6	Identifying (Unknown)	4	5.000	0.000	0.000	3	0.30	0.000	4	0.20	0.000	5	0.45	0.000	6	0.05	0.000			
7	Prioritizing	4	1.000	0.000	0.000	8	0.15	0.000	9	0.70	0.000	10	0.10	0.000	11	0.50	0.000			
8	Deciding (Self Engage)	3	4.000	0.000	0.000	19	0.70	0.000	20	0.10	0.000	21	0.20	0.000						
9	Deciding (CFF)	1	4.000	0.000	0.000	15	1.00	0.000												
10	Deciding (RHO)	1	4.000	0.000	0.000	12	1.00	0.000												
11	Deciding (Bypass)	1	4.000	0.000	0.000	1	1.00	0.000												
12	RHO to AH-64	2	5.000	0.000	0.000	13	0.95	0.000	14	0.05	0.000									
13	RHO to AH-64 rec'd	1	1.000	0.000	0.000	Apache	1.00	0.000												
14	RHO to AH-64 not rec'd	1	3.000	0.000	0.000	12	1.00	0.000												
15	Preparing ATHS Msg	1	N	40.000	5.000	16	1.00	0.000												
16	Sending to AFATDS	2	7.000	0.000	0.000	18	0.90	0.000	17	0.10	0.000									
17	AFATDS not rec'd	1	8.000	0.000	0.000	16	1.00	0.000												
18	AFATDS rec'd	1	1.000	0.000	0.000	Artillery	1.00	0.000												
19	Engage w/ Hellfire	5	3.000	0.000	0.000	22	0.85	20.000	23	0.05	20.000	24	0.04	20.000	25	0.05	20.000	26	0.010	20.000
20	Engage w/ Rockets	5	5.000	0.000	0.000	22	0.50	10.000	23	0.15	10.000	24	0.15	10.000	25	0.10	10.000	26	0.100	10.000
21	Engage w/ 30mm	5	4.000	0.000	0.000	22	0.20	8.000	23	0.30	8.000	24	0.20	8.000	25	0.10	8.000	26	0.200	8.000
22	Target Destroyed	1	5.000	0.000	0.000	1	1.00	0.000												
23	Target Mobility Kill	1	5.000	0.000	0.000	1	1.00	0.000												
24	Target Commo Kill	2	7.000	0.000	0.000	1	0.80	0.000	8	0.20	0.000									
25	Target Firepower Kill	1	5.000	0.000	0.000	1	1.00	0.000												
26	Target Missed	2	3.000	0.000	0.000	8	0.90	0.000	11	0.10	0.000									
27	Enroute to FARP	1	N	1200	60	FARP	1.00	0.000												
28	At Waypoint	1	1.000	0.000	0.000	30	1.00	999900												
29	Target Undetected	1	1.000	0.000	0.000	1	1.00	999999												
30	End of Mission	1	999999	0.000	0.000	30	1.00	1.000												

Figure A-2. ***Longbow*** **Network**

Longbow2 Node #	Name	Out Degree	Cost	Par 1	Par 2	Connected to ... Node	Prob	Cost	Node	Prob	Cost
15	Preparing RFO	1	U	1.000	2.000	16	1.000	0.000			
16	Sending to AFATDS	2	7.000	0.000	0.000	18	0.900	0.000	17	0.10	0.000

Figure A-3. ***Longbow2*** **Network**

Artillery Node #	Receive CFF	Out Degree	Cost	Par 1	Par 2	Connected to ... Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost
1	Analyzing Mission	1	5.000	0.000	0.000	2	1.000	0.000						
2	Sending to Guns	3	15.000	0.000	0.000	6	0.900	0.000	3	0.050	0.000	4	0.050	0.000
3	Sending Again	1	5.000	0.000	0.000	2	1.000	0.000						
4	Waiting for Cmd	1	N	30.000	5.000	5	1.000	0.000						
5	Cmd Rec'd	1	1.000	0.000	0.000	6	1.000	-10.000						
6	Firing Rounds	2	N	30.000	3.000	7	0.010	0.000	8	0.990	0.000			
7	Miss Fired (1 tube)	1	1.000	0.000	0.000	8	1.000	0.000						
8	Rounds Impact	1	10.000	0.000	0.000	Longbow	1.000	999999						

Figure A-4. ***Artillery*** **Network**

Info Node #	Name	Out Degree	Cost	Par 1	Par 2	Connected to ... Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost
1	Receive Info	3	1.000	0.000	0.000	2	0.300	0.000	3	0.400	0.000	4	0.300	0.000
2	Rec'd Updated Tgt	1	1.000	0.000	0.000	1	1.000	999999						
3	Rec'd Red S.A.	1	1.000	0.000	0.000	1	1.000	999999						
4	Rec'd Blue S.A.	1	1.000	0.000	0.000	1	1.000	999999						

Figure A-5. ***Info*** **Network**

Apache		Out				Connected to ...														
Node #	Name	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost
1	Target Located	3	5.000	0.000	0.000	2	0.700	0.000	3	0.100	0.000	4	0.200	0.000						
2	Engage w/ Hellfire	5	3.000	0.000	0.000	5	0.850	20.000	6	0.050	20.000	7	0.040	20.000	8	0.050	20.000	9	0.010	20.000
3	Engage w/ Rockets	5	5.000	0.000	0.000	5	0.500	10.000	6	0.150	10.000	7	0.150	10.000	8	0.100	10.000	9	0.100	10.000
4	Engage w/ 30mm	5	4.000	0.000	0.000	5	0.200	8.000	6	0.300	8.000	7	0.200	8.000	8	0.100	8.000	9	0.200	8.000
5	Target Destroyed	1	5.000	0.000	0.000	Longbow	1.000	0.000												
6	Target Mobility Kill	4	5.000	0.000	0.000	Longbow	0.200	0.000	2	0.600	0.000	3	0.100	0.000	4	0.100	0.000			
7	Target Commo Kill	4	7.000	0.000	0.000	Longbow	0.100	0.000	2	0.600	0.000	3	0.100	0.000	4	0.200	0.000			
8	Target Firepower Kill	4	5.000	0.000	0.000	Longbow	0.300	0.000	2	0.500	0.000	3	0.100	0.000	4	0.100	0.000			
9	Target Missed	4	3.000	0.000	0.000	Longbow	0.100	0.000	2	0.600	0.000	3	0.100	0.000	4	0.200	0.000			

Figure A-6. ***Apache*** **Network**

FARP		Out				Connected to ...					
Node #	Name	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost
1	Arrives at FARP	1	30.000	0.000	0.000	3	0.500	30.000	2	0.500	0.000
2	in Holding Area	1	N	300.000	60.000	3	1.000	30.000			
3	Refueling	2	N	300.000	60.000	4	0.900	30.000	2	0.100	0.000
4	Rearming	1	N	420.000	60.000	Longbow	1.000	0.000			

Figure A-7. ***FARP*** **Network**

Malfunction		Out				Connected to ...														
Node #	Name	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost
1	Malfunction	5	1.000	0.000	0.000	2	0.200	0.000	3	0.200	0.000	4	0.200	0.000	5	0.200	0.000	6	0.200	0.000
2	Electrical Problem	4	5.000	0.000	0.000	7	0.600	0.000	8	0.200	0.000	9	0.100	0.000	10	0.100	0.000			
3	Armament Problem	4	5.000	0.000	0.000	7	0.600	0.000	8	0.200	0.000	9	0.100	0.000	10	0.100	0.000			
4	Flight Control Problem	4	3.000	0.000	0.000	7	0.300	0.000	8	0.250	0.000	9	0.400	0.000	10	0.050	0.000			
5	Engine Problem	4	4.000	0.000	0.000	7	0.300	0.000	8	0.400	0.000	9	0.200	0.000	10	0.100	0.000			
6	Aircrew Problem	3	2.000	0.000	0.000	7	0.700	0.000	8	0.200	0.000	9	0.100	0.000						
7	Continue Mission	1	E	0.000	0.000	1	1.000	999999												
8	Return to Base	1	1.000	0.000	0.000	11	1.000	0.000												
9	Land	1	1.000	0.000	0.000	11	1.000	0.000												
10	Aircraft Destroyed	1	1.000	0.000	0.000	11	1.000	0.000												
11	End of Mission	1	1.000	0.000	0.000	11	1.000	999999												

Figure A-8. ***Malfunction*** **Network**

Detected		Out				Connected to ...														
Node #	Name	Degree	Cost	Par 1	Par 2	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost	Node	Prob	Cost
1	Detected by Enemy	1	1.000	0.000	0.000	2	1.000	0.000												
2	Enemy Fires	5	3.000	0.000	0.000	3	0.200	0.000	4	0.100	0.000	5	0.100	0.000	6	0.500	0.000	7	0.100	0.000
3	Evasive Maneuvers	4	2.000	0.000	0.000	4	0.300	0.000	5	0.300	0.000	6	0.300	0.000	7	0.100	0.000			
4	Dispense Chaff	2	1.000	0.000	0.000	6	0.400	0.000	7	0.600	0.000									
5	Dispense Flares	2	1.000	0.000	0.000	6	0.400	0.000	7	0.600	0.000									
6	Hit By Enemy	1	1.000	0.000	0.000	Malfunction	1.000	0.000												
7	Enemy Misses	2	5.000	0.000	0.000	Longbow	0.900	999999	2	0.100	0.000									

Figure A-9. ***Detected*** **Network**

APPENDIX B. MANAGEMENT WORKSHEETS

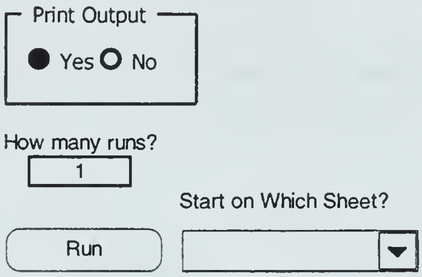

Figure B-1. Sample *Menu* Worksheet

ID #	Type	#	X - Coord	Y- Coord	Speed	Radians	Degrees	Detected at Range	Detected	Killed? 1	2	3	4	5	6	7
1	Longbow	1	13009	50932	61.728	0.000	0	N/A	N	N	N	N	N	N	N	N

Figure B-2. Sample *Friendly* Worksheet

						Direction		Detected		Killed?						
ID #	Type Tgt	# Veh	X - Coord	Y- Coord	Speed	Radians	Degrees	at Range	Detected?	1	2	3	4	5	6	7
1	IFV	1	09464	05167	3.005	1.652	95	2225	N	N	N	N	N	N	N	N
2	IFV	4	06985	08863	2.447	2.998	172	3451	N	N	N	N	N	N	N	N
3	IFV	6	04726	08540	3.717	2.095	120	3420	N	N	N	N	N	N	N	N
4	IFV	4	06901	07482	3.752	4.306	247	3497	N	N	N	N	N	N	N	N
5	IFV	5	09018	07675	2.518	1.770	101	3933	N	N	N	N	N	N	N	N
6	IFV	4	13916	07248	3.113	2.897	166	2522	N	N	N	N	N	N	N	N

Figure B-3. Sample *Enemy* Worksheet

enemy ID	Range	X	Y	Detected Speed	Direction	Time	Engaged	Bypass
8	2977.90	2510.45	4291.40	2.19	3.92	97.51	N	
9	5853.96	4562.12	3176.28	1.34	2.63	11.11	N	
4	7414.71	2993.57	5379.85	1.06	4.50	114.19	N	

Figure B-4. Sample *DetectList* Worksheet

Sheet	Node	Event Name	Begin Times Sec	Begin Times Min
Longbow1	1	Searching	0.0	0.00
Longbow1	28	At Waypoint	89.1	1.49
Longbow1	2	Friendly 1 Detects Enemy 2	149.5	2.49
Longbow1	3	Identifying (Enemy)	150.5	2.51
Longbow1	7	Prioritizing	151.5	2.53
Longbow1	9	Deciding (CFF)	152.5	2.54
Longbow1	15	Preparing ATHS Msg	156.5	2.61
Longbow1	16	Sending to AFATDS	197.1	3.28
Longbow1	18	AFATDS rec'd	204.1	3.40
Arty	1	Analyzing Mission	205.1	3.42
Longbow1	1	Searching	205.1	3.42
Arty	2	Sending to Guns	210.1	3.50
Longbow1	28	At Waypoint	211.6	3.53
Longbow1	29	Friendly 1 UnDetects Enemy 2	222.4	3.71
Arty	6	Firing Rounds	225.1	3.75
Arty	8	Rounds Impact	247.1	4.12
Longbow1	28	At Waypoint	334.1	5.57
Longbow1	28	At Waypoint	456.6	7.61
Detected	1	Detected by Enemy	1116.6	18.61
Detected	2	Enemy Fires	1117.6	18.63
Detected	6	Hit By Enemy	1120.6	18.68
Malfunction	1	Malfunction	1121.6	18.69
Malfunction	5	Engine Problem	1122.6	18.71
Malfunction	7	Continue Mission	1126.6	18.78
Longbow1	28	At Waypoint	1716.3	28.60
Info	1	Receiving Info	2263.9	37.73
Info	3	Rec'd Red S.A.	2264.9	37.75
Longbow1	28	At Waypoint	2975.9	49.60
Longbow1	28	At Waypoint	3098.4	51.64
Longbow1	28	At Waypoint	3220.9	53.68
Longbow1	28	At Waypoint	3343.4	55.72
Longbow1	28	At Waypoint	3433.5	57.23

Figure B-5. Sample *Output* Worksheet

Begin Time	Event	Sheet	Node	Param 1	Param 2	Param 3	Param 4
172.18	Identifying (Enemy)	Longbow1	3				
211.60	At Waypoint	Longbow1	28				
216.19	Friendly 1 UnDetects Enemy 1	Longbow1	29		1		
813.43	Detected by Enemy	Detected	1				
2287.07	Receiving Info	Info	1				
14003.55	Malfunction	Malfunction	1				
999999.00	End						

Figure B-6. Sample *EventList* Worksheet

Longbow

	Start Location		End Location		FARP Location
x-coord:	7500	x-coord:	7500	x-coord:	3000
y-coord:	0	y-coord:	0	y-coord:	0

)et Range:	N/A	meters	speed:	120	knots
TLE:	5	meters		62	meter/sec

Malfunction every: 240 minutes

Receive Info every: 45 minutes

	Way Points		Next
start	7500	0	
1	2000	0	X
2	2000	7500	
3	2000	15000	
4	2000	22500	
5	7500	100000	
6	13000	22500	
7	13000	15000	
8	13000	7500	
9	13000	0	
end	7500	0	
	X	Y	

Figure B-7. Sample *Parameter* Worksheet (Longbow)

Artillery | Target | Longbow

Artillery

x-coord:	7500	15000 is center
y-coord:	0	
Lethality:	8.00	Gauss A
	1.00	Gauss Po

Rnds to Fire if ...

1 Veh	12
2 Veh	24
3 Veh	30
4 Veh	36
5 Veh	36
6 Veh	36
7 Veh	36

Relative Aim Points

	Aim Pt 1	Aim Pt 2	Aim Pt 3	Aim Pt 4	
1Veh	0	0	0	0	x
	0	0	0	0	y
2 veh	0	0	0	0	x
	0	0	0	0	y
3 Veh	0	35	35	0	x
	0	35	35	0	y
4 Veh	17	17	52	52	x
	17	17	17	17	y
5 Veh	35	35	105	105	x
	10	10	10	10	y
6 Veh	35	35	140	140	x
	10	10	10	10	y
7 Veh	35	35	140	140	x
	10	10	10	10	y

	BE (Sigma)			
Distance	Range	Delection	TOF	Distance
4	10	4	10	4
6	14	5	16	6
8	18	6	22	8
10	24	7	27	10
12	30	8	33	12
14	40	8.5	39	14
16	50	9	45	16
18	52	9.5	51	18
20	54	10	52	20
22	57	10.5	53	22
24	60	11	54	24
26	64	11.3	55	26
28	66	11.7	56	28
9999	70	21	57	9999
km's	meters	meters	sec	km's

Target

Enemy Groups: 10

Relative Vehicle Positions

	x	y
Veh 1	0	0
Veh 2	35	35
Veh 3	70	0
Veh 4	105	35
Veh 5	140	0
Veh 6	175	35
Veh 7	210	0

X - Coord	Min	2000	
	Max	14000	
Y - Coord	Min	5000	
	Max	10000	
Speed	Min	5	kph = 1.39 meter/sec
	Max	15	kph = 4.17 meter/sec
	Sigma	2	kph = 0.56 meter/sec
Direction	Min	90	degrees
	Max	270	degrees
	Sigma	2	degrees
		North is 0	

Figure B-8. Sample *Parameter* Worksheet (Artillery & Target)

APPENDIX C. SUBROUTINES & FUNCTIONS

"Run" Subroutine

After setting the initial parameters on the *Parameters* sheet, the user clicks the "*Run*" command button on the *Menu* worksheet to begin the simulation. This starts the *Run* subroutine. The following algorithm describes the actions completed by *Run* (words in *italics* indicate calls to other subroutines or functions):

Begin *Run* Subroutine
    Initialize all variables and worksheets
    Do until number of runs equals requested number
        Reset selected variables
        initiateSheets
        Do until next event time > 999998 (terminal node)
            Get next event from event list
            Move all friendly and enemy entities
            Execute specified subroutines
            Determine *nextNode* (event) to schedule
            Add to event list
            Remove current event from list
            SortEventList
        Loop / Next event
        Capture data
    Loop / Next run
End

"initiateSheets" Subroutine

When called by *Run*, this subroutine clears the *Output, Stats, Enemy, Friendly,DetectList, eventList* and *Temp* worksheets; inserts a row counting formula into the *eventList, Temp, Enemy* and *Friendly* worksheets; schedules the enemy's first detection, the first malfunction, the first receipt of information and an "End of Mission" event.

"nextNode" Subroutine

Given the current network name and the current number of the occupied node, this subroutine determines the next node to add to the event list. The following algorithm describes this process:

```
Begin nextNode Subroutine
    Determine time spent at current node (from node cost on worksheet)
        Call random number generator, if required, using parameters 1 and 2.
    Random = draw from uniform (0,1) distribution
    Cumulative Probability (CProb) = 0
    Do while Random > CProb
        CProb = CProb + probability of next adjacent node in row
        If Random < CProb then nextNode = next adjacent node
    Loop
    nextTime = current time + time at current node + "arc" time to next Node
    Return nextNode and nextTime
End
```

The *Run* subroutine schedules the nextNode at the nextTime on the *eventList* worksheet.

"setPositions" Subroutine

Based upon the user-input parameters from the *Parameters* worksheet, this subroutine defines and records the starting locations and conditions for all enemy and friendly entities. These values are maintained in the *Enemy* and *Friendly* worksheets. A portion of each are shown in Figures C-1 and C-2

						Direction		Detected		Killed?						
ID #	Type Tgt	# Veh	X - Coord	Y- Coord	Speed	Radians	Degrees	at Range	Detected	1	2	3	4	5	6	7
1	IFV	7	02979	11649	3.499	4.030	231	7539	N	N	N	N	N	N	N	N
2	IFV	4	05121	14543	3.157	2.027	116	5198	N	N	N	N	N	N	N	N
3	IFV	5	03727	07371	3.076	3.930	225	6266	N	N	N	N	N	N	N	N
4	IFV	2	04433	09396	2.889	4.440	254	4711	N	N	N	N	N	N	N	N
5	IFV	1	09322	07546	4.088	4.708	270	5097	N	N	N	N	N	N	N	N
6	IFV	3	00838	08724	3.742	3.087	177	7934	N	N	N	N	N	N	N	N
7	IFV	6	06258	08497	3.295	3.021	173	5542	N	N	N	N	N	N	N	N
8	IFV	4	04209	08006	3.380	2.632	151	7808	N	N	N	N	N	N	N	N
9	IFV	7	00839	09742	3.208	3.621	207	6207	N	N	N	N	N	N	N	N
10	IFV	2	04833	09809	3.948	2.451	140	5465	N	N	N	N	N	N	N	N

Figure C-1. Sample *Enemy* Worksheet

						Direction		Detected		Killed?						
ID #	Type	#	X - Coord	Y- Coord	Speed	Radians	Degrees	at Range	Detected	1	2	3	4	5	6	7
1	Longbow	1	07500	13747	61.728	0.000	0	N/A	N	N	N	N	N	N	N	N

Figure C-2. Sample *Friendly* Worksheet

"Move" Subroutine

At the beginning of each event, this subroutine moves all entities that have a speed greater than zero. The new location is based upon the time elapsed since the last event (in seconds), the rate of movement (meters/second), and the direction of movement (radians; 0 is north). Locations are maintained on the *Enemy* and *Friendly* sheets.

"atWayPoint" Subroutine

When a Longbow reaches one of the user defined waypoints, this subroutine adjusts the aircraft's course toward the next waypoint and reschedules all detections. If the aircraft is at the last waypoint, the *endMission* subroutine is called. An "X" indicating the next waypoint is provided on the *Parameters* sheet next to the waypoint matrix.

"schedDetect" Subroutine

When called, this subroutine evaluates all entities to determine if a friendly unit will detect an enemy unit. A Longbow will detect an enemy (with probability of 1.0) if the distance between them is less than a specified range. The specified range is a random value that implicitly accounts for battlefield obscurants, concealment, and other factors that affect the probability of detection. The subroutine *solveQuad* determines if and when the Longbow will be within that range. If the Longbow will be within the detection range of a vehicle, *schedDetect* adds the appropriate events to the event list. A detection event is added at the time the Longbow initially enters the range. An "un-detect" event is added at the time the Longbow is no longer within detection range. This un-detect event signifies the time at which the Longbow is no longer able to detect the enemy.
Figure C-3 illustrates the detection process.

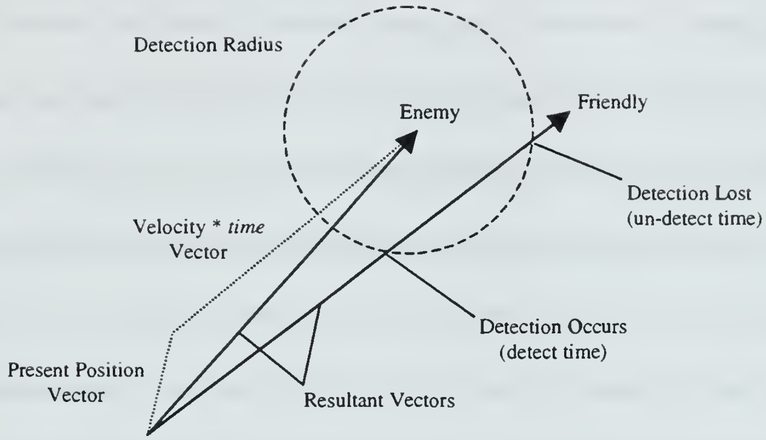

Figure C-3. Scheduling Detections

"solveQuad" Subroutine

This subroutine returns the time values that are solutions to the quadratic equation used to schedule detections and "un-detections". The detection times can be found by solving the following equation, which can be expressed as a quadratic equation, for *time*:

$$\left\| \begin{pmatrix} P_{fx} \\ P_{fy} \end{pmatrix} + time \bullet \begin{pmatrix} V_{fx} \\ V_{fy} \end{pmatrix} - \begin{pmatrix} P_{ex} \\ P_{ey} \end{pmatrix} - time \bullet \begin{pmatrix} V_{ex} \\ V_{ey} \end{pmatrix} \right\| = \text{Detection Range}$$

Here, the P vectors refer to the present position vectors for the friendly (f) and enemy (e) elements, and the V vectors refer to their velocity vectors (Figure C-3). Solving for time is accomplished by using the standard equations for the solutions of a quadratic equation:

$$detect\ time = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

and

$$un\text{-}detect\ time = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

The calling subroutine (*schedDetect*) will only call *solveQuad* if (b^2-$4ac$) is greater than or equal to zero. A detection occurs only if there exists two real solutions for *time*, one of

which must be greater than zero. These times define a “detection window”. If one value is less than zero, the detection has already occurred (value less than zero) but the un-detection will occur in the future (value greater than zero). If both values are greater than zero, the detection will occur in $time_{\text{shorter}}$ units of time and the un-detection will occur in $time_{\text{longer}}$ units of time. $time_{\text{shorter}}$ refers to the lower *time* solution value; $time_{\text{longer}}$ refers to the larger *time* solution value. If both values are less than zero, the detection and un-detection events would have occurred in the past, so no events are scheduled. Figure C-3 shows the relationship of these times in the detection process.

“detection” Subroutine

When a detection event occurs, this subroutine records all pertinent information for the detected enemy: enemy identification number, time, location, and rate and direction of movement. To simulate the random movement of the enemy vehicles, the recorded rate and direction of movement are the *perceived* values, not the actual values. These perceived values are random observations from two Normal distributions that have means equal to the actual rate and direction. The standard deviations for these distributions are obtained from user-input values in the “Target” section of the *Parameters* worksheet. The *predictXY* subroutine uses these perceived values to predict aim points for the artillery.

“predictXY” Subroutine

Given a specific target’s x and y coordinates when detected, its perceived speed and direction of movement when detected and the time since detection, this subroutine

predicts the current x and y coordinates of the target. An underlying assumption is that the target has been moving at a constant (perceived) speed and in a constant (perceived) direction since detection. As previously discussed, the perceived rate and direction of movement are not the same as the actual rate and direction of movement.

"shootArty" Subroutine

This subroutine simulates the firing and impact of artillery rounds. An algorithm describing the process follows (*italics* indicate subroutines or functions):

```
Begin shootArty subroutine
    Determine x target location error from Norm (0, [TLE]) distribution
    Determine y target location error from Norm (0, [TLE]) distribution
    For each round fired
        Determine at which aim point the round is aimed
        Determine coordinates of the aim point
        Determine the x and y ballistic error of the round (getBE)
        Define impact coordinates for the round
        For each vehicle in the target group
            Determine actual vehicle coordinates
            getDistance from the impact point to the vehicle location
            Determine if this vehicle was killed (BDA); change state as required
        Next vehicle
    Next round
End subroutine
```

Figure C-4 illustrates the artillery scenario and the effect of a target group moving at a non-constant speed and direction.

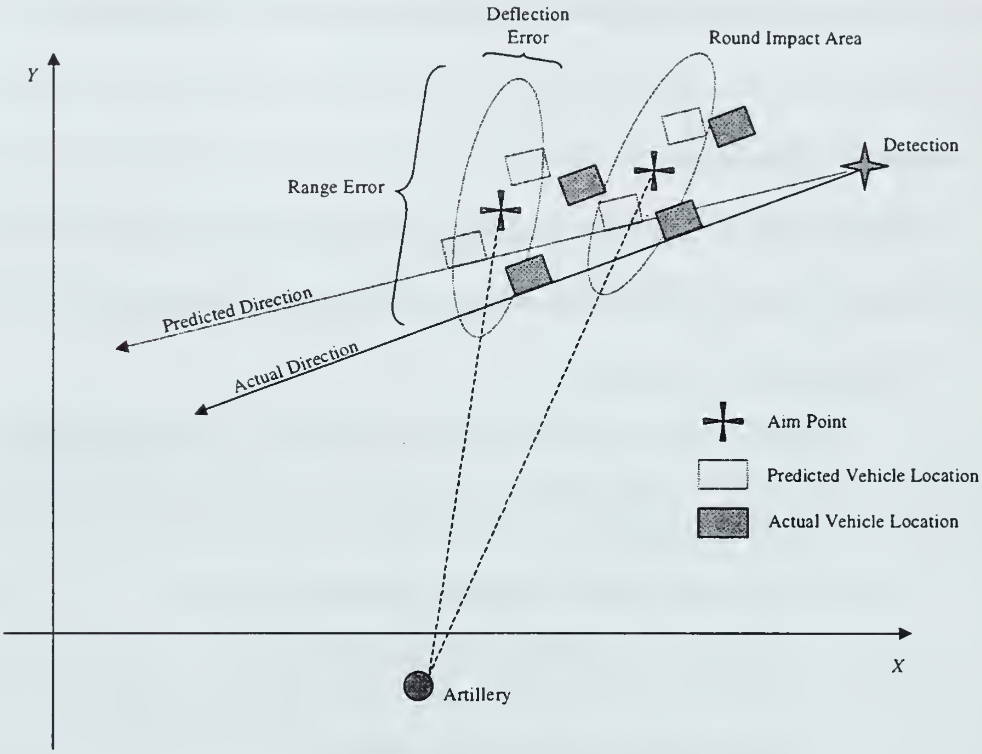

Figure C-4. Target Engagement with Artillery

"BDA" Function

This function returns a boolean indicating whether a specific artillery round has "killed" an enemy vehicle (true) or not (false). This determination is based upon the range from the impact point to the vehicle and a Gaussian lethality function. The user provides the parameters P_o (probability of kill given a direct hit) and a (lethal area) for the function on the *Parameters* worksheet.

"Linked" Subroutine

This subroutine reenacts an artillery engagement using an RFHO instead of a ATHS message. After resetting the target and Longbow to the locations, the simulation is run on the *temp* worksheet until the artillery rounds have impacted. The following algorithm describes this process:

Begin *Linked* Subroutine
- Set current network equal to *Longbow2*
- Set current node equal to 15 ("Preparing RFHO")
- Set time equal to the time the Longbow began preparing the call-for-fire.
- Position target and Longbow back to the locations occupied when the target was detected.
- Reconstitute any "killed" enemy vehicles (*ResetKills*)
- *Move* target and Longbow to reflect correct positions at current time.
- "Run" simulation on *temp* event list until artillery rounds impact

End

A separate counter within the *Run* subroutine captures the number of vehicles killed.

Norm(mean, standard deviation) Function

This function utilizes the polar method [Ref. 8, p. 491] to return one random observation from a normal distribution having the given parameters. The Visual Basic for Excel *rnd*() function is used to draw the random uniform (0,1) values required and to decide which of the two random values produced by the polar method to return.

Weibull(α,β) Function

Random observations from a Weibull distribution with parameters α and β are obtained through the inverse Weibull function: *Value* = $\beta*(-ln(\text{rnd}()))^{1/\alpha}$. Again, the *rnd*() function provides the uniform (0,1) required. This function also provides random observations of the exponential (λ) distribution by assigning $\alpha = 1$ and $\beta = {}^{1}/_{\lambda}$.

APPENDIX D. SUMMARY OF RESULTS

OBSERVED VEHICLE KILLS PER ENGAGEMENT

	Prep Time	1.5 s	20 s	40 s	60 s
Lethal Area / Type	Kills	Count	Count	Count	Count
	0	1387	1407	1480	1518
6 m ATHS	1	568	553	490	447
	2	45	40	29	35
	3	0	0	1	0
	0	1387	1369	1403	1354
6 m RFHO	1	568	584	553	584
	2	45	47	43	62
	3	0	0	1	0
	0	1069	1121	1216	1309
8 m ATHS	1	790	764	673	600
	2	136	114	109	89
	3	5	1	2	2
	0	1069	1020	1076	1084
8 m RFHO	1	790	858	775	782
	2	136	122	147	132
	3	5	0	2	2
	0	788	859	952	1086
10 m ATHS	1	919	886	823	742
	2	286	250	221	168
	3	7	5	4	4
	0	788	755	742	810
10 m RFHO	1	919	940	928	881
	2	286	292	322	299
	3	7	13	8	10

OBSERVED DIFFERENCES (RFHO KILLS - ATHS KILLS) PER ENGAGEMENT

	Prep Time	1.5 s	20 s	40 s	60 s
Lethal Area	RFHO - ATHS	Count	Count	Count	Count
	-2	0	3	10	11
	-1	0	155	199	228
6 m	0	2000	1644	1494	1348
	1	0	190	284	385
	2	0	8	13	28
	-3	0	0	0	1
	-2	0	16	24	23
	-1	0	145	211	226
8 m	0	2000	1573	1366	1253
	1	0	248	362	452
	2	0	18	36	44
	3	0	0	1	1
	-3	0	1	0	1
	-2	0	11	24	18
	-1	0	144	186	210
10 m	0	2000	1535	1296	1178
	1	0	287	435	518
	2	0	22	59	75
	3	0	0	0	0

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